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JOURNAL OF THE AMERICAN
ACADEMY OF ARTS AND SCIENCES

SCIENTIFIC LITERACY

A. B. Arons
J. Myron Atkin
Barton Childs
Stephen R. Graubard
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Faith Hickman
Philip W. Jackson
John G. Kemeny
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Scientific Literacy

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Contents

v Preface

Herbert J. Walberg
1 Scientific Literacy and Economic Productivity in International Perspective

Jon D. Miller
29 Scientific Literacy: A Conceptual and Empirical Review

Kenneth Prewitt
49 Scientific Illiteracy and Democratic Theory

David Hawkins
65 Nature Closely Observed

A.B. Arons
91 Achieving Wider Scientific Literacy

Mary Budd Rowe
123 Science Education: A Framework for Decision-Makers

Philip W. Jackson
143 The Reform of Science Education: A Cautionary Tale

J. Myron Atkin
167 The Improvement of Science Teaching

Barton Childs and Faith Hickman
189 Human Genetics: One Approach to Scientific Literacy

John G. Kemeny
211 The Case for Computer Literacy

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Stephen R. Graubard
231 Nothing to Fear, Much to Do

249 Notes on Contributors

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Preface to the Issue: "Scientific Literacy"

"THE PAST IS A FOREIGN COUNTRY; they do things differently there." This idea, originally expressed by L.P. Hartley in *The Go-Between,* could, with only very slight modifications, be said to describe the attitudes of many in this country today with respect to science. To say that science is a mystery for great numbers—that it appears to be largely inaccessible even to men and women who believe themselves educated—and that this condition is scarcely improving, is now commonly accepted. Why such ignorance or "illiteracy" is hazardous, how it impedes social and economic progress, what it does to make certain individuals feel alienated and uncomfortable, never wholly at ease even when not required to cope with complex machines or technologies, and why such illiteracy has larger implications for the society as a whole, are only a few of the questions raised in this issue of *Daedalus.*

It cannot be surprising that much of the issue addresses the question of how such illiteracy can be combated, what can be done to reduce it. As in Great Britain, where the Royal Society has recently published a sobering report, "Science Education 11–18 in England and Wales," there is a constantly repeated refrain in these *Daedalus* pages that "we do not appreciate fully the extent to which scientific education is positively valuable in careers outside the scientific and technological fields as popularly understood." Indeed, some would go so far as to say that the consequences of scientific illiteracy are not principally vocational or professional; there are other even more substantial losses. The Royal Society's study group insists that "there is a particular need to reiterate the merits of a strongly scientific education for people likely to be concerned with affairs generally, and not only with their technological aspects."

If some choose to dismiss such statements as rhetorical, not providing obviously useful information on precisely how children—let alone adults—can be instructed in science, how they can be made aware of its importance, how they and their teachers can achieve some modicum of self-confidence in doing science, in trying to understand its basic concepts, its content, not to speak of its methods

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and applications, this may derive from greater flaws in our educational system that are all too rarely acknowledged or examined. A letter at hand, arriving literally at the moment this preface is being written, argues that the "problem is more than a lack of mathematical training"; my correspondent speaks of "an almost complete lack of the discipline and ability that is required to follow a sequential logical argument that requires more than a few steps." If this condition is common, if it is common in higher educational institutions that are still vastly oversubscribed today—a very uncommon thing—that still turn away many students for every one they admit, what must the condition be in more ordinary colleges and universities, let alone in schools and in the workplace? It is easy to say, as the Royal Society's report does, that "courses should be firmly differentiated in difficulty and treatment, to accommodate different ability ranges." What, however, is the practical import of the additional statement: "This should not, however, be taken to mean that there is one kind of science for the less able and another for the more able. The science taught may be easy or difficult as appropriate, but it should always be genuine science."

How are those deputed to develop science curricula helped by such a caveat? How can they interpret it? What, indeed, can they learn from past experience? In this country, where so much effort was made to improve science instruction after the alarm produced by the Soviets' success in launching *Sputnik,* what does that whole experience teach? What, indeed, are the lessons learned from the past more generally, or from others?

As will become obvious to those who read this issue in its entirety, there is common agreement that the situation is not improving; there is no analogous agreement on what can or must be done to improve it, and why one strategy is more imperative or more likely to succeed than another. No effort has been made to suppress (or minimize) the extent of the perceptual and practical differences that are communicated in these pages. They tell something of the debate raging today, not only in educational circles, but outside as well. The misgivings and concerns expressed here are not unique to the United States; indeed, their significance may derive from the fact that they are so common in that part of the world which deems itself developed.

Thanks need to be expressed to the National Science Foundation for support of this project.* It is to be hoped that this volume will contribute to a debate that can only intensify as others also produce

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their reports, for the issue of "scientific literacy," however defined, can only become more preoccupying as additional evidence proving educational insufficiency is gathered. The question, obviously, is how American society in the coming years will seek to cope with the issue, how it will perceive its options, and how it will act.

S.R.G.

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Herbert J. Walberg

Scientific Literacy and Economic Productivity in International Perspective

THE SCIENTIFIC LITERACY of American youth, their mastery of the basic knowledge and skills of communication in science, is a problem of grave national concern. Their achievement test scores in science and mathematics of a decade or two ago compared unfavorably with those of youth in other industrialized countries, and since that time, have declined substantially. Yet our understanding of how knowledge and skills are acquired is continually increasing, and it is quite within the power of our society to improve scientific literacy for both the common and individual good.

Scientific literacy, of course, is related to general literacy, the ability to read and write. This is a broad and growing area of public concern, made especially so by the enormous increase in the percentage of all U.S. workers in the "knowledge industries"—those that produce, process, and distribute information goods and services—which rose from about 5 percent in 1860 to about 50 percent in 1980.[1] Estimates, however, indicate that about 20 percent of all American seventeen-year-olds were verbally illiterate in 1975, having failed to respond correctly to simple written questions about everyday life in our modern society.[2] Because they are less well informed, many of these young people will be unable to participate intelligently in either civic affairs or in the productive sector of the economy, in which half the work force is involved.

To be sure, the picture at the higher levels of science is much rosier. Of the nine Nobel prizewinners in the sciences in 1981, seven were faculty members at American research universities, and approximately 40 percent of the world's recent literature in science is the result of American research efforts. Moreover, the general ability scores of high-school seniors intending to major in science and math-

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ematics in college rose slightly from 1960 to 1972, and the supply of qualified scientists and engineers is likely to be more than adequate to meet the demand throughout the 1980s.[3] In the long run, however, both support for, and the benefits of, American science will depend in part on the scientific literacy and attitudes of those who are not specialists—adults and youths alike.

The recent research findings of Theodore W. Schultz and Herbert A. Simon, two contemporary Nobel prizewinners in economics, are relevant to the problem of scientific literacy. Their works summarize a considerable amount of plausible and consistent evidence on the pecuniary and other benefits of literacy, as well as on how it is psychologically acquired. This evidence is significant for two reasons. First, although literacy may be considered as a consumatory end in its own right, it may require further justification as an investment or a means to other ends such as economic productivity and welfare. Second, its improvement will depend on our understanding of how literacy is acquired and measured.

ECONOMIC ASPECTS OF LITERACY

In his research, Schultz shows how investments in education and other forms of human capital raise economic productivity. He cites a number of studies which reveal that throughout the world—including the less industrialized countries—the abilities of people, together with advances in knowledge, have raised their economic standing, and with it, other aspects of life that contribute to their overall sense of well-being. Improved child care, information and skills acquired in school and through work experience, and other human investments in health and education have paid high economic returns. The wealth of a nation, as Adam Smith held two centuries ago, depends in part on the skills and knowledge of its people.

Schultz points out that during the period from 1900 to 1970, when the U.S. economy grew enormously, the total financial stock of education embodied in the labor force increased thirteenfold, from $63 to $815 billion. This vast increase in investment did not, in general, result in observable diminishing returns; education, it appears, still pays. Growth rates in economic productivity for the United States—and England—however, have fallen behind those of other countries,[4] notably Japan and the Federal Republic of Germany, ap-

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parently because of lagging or misallocated investments in human capital in recent decades.

Science, Schultz says, is a special form of "human-made" capital; it is embodied in scientific literature, in economically productive developments such as computers and hybrid corn, and in human beings. To broaden knowledge of it requires the investment of scarce resources—mainly the time and effort of people—to gain future returns and satisfactions. The improved literacy—scientific, technological, and other kinds—that is the result of such sacrifices has been far more important to the industrialization of the West than is generally acknowledged. And it will continue to be as vital to the well-being of postindustrial or information societies as it is for low-income countries seeking to modernize.

PSYCHOLOGICAL ASPECTS OF LITERACY

Until recently, the acquisition of scientific literacy and the enlargement of general knowledge on the part of the individual had only been intuitively understood and was best observed in extreme cases. Contrary to the notion of instant "creativity" that was popular in the 1960s, distinguished scientific accomplishment is a matter of opportunity and of continuous and concentrated effort over at least a decade. When Newton was asked how he had managed to surpass the discoveries of his predecessors, in both quantity and quality, he replied, "By always thinking about them." Add to this the comment of Gauss that "if others would but reflect on mathematical truths as deeply and continuously as I have, they would make my discoveries," and it becomes apparent that "instant" scientific discoveries are many long years in the making.

So, too, are accomplishments in many other areas. Psychological studies of the lives of eminent painters, writers, musicians, philosophers, religious leaders, and scientists of previous centuries, as well as prizewinning adolescents in this country today, reveal early, intense concentration on previous work in their fields, often to the near-exclusion of other activities. It appears, though, that science and mathematics, because of their highly specialized and abstract symbolism, may require the greatest concentration and perseverance.[5]

The same fundamental thought processes, moreover, appear to be required in both elementary and advanced science, as Simon and his colleagues have shown.[6] The development of literacy, the acquisition

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of information, and the problem-solving of beginners differ in degree rather than in kind from the mental activities of experts. The scarce resources are opportunity and concentration rather than the amount of information available or the processing capacity of the mind, both of which, for practical purposes, are unlimited.

Aside from motivation, external opportunities, and incentives, the major constraints on the acquisition of knowledge are the few items of information, perhaps two to seven, that can be held to immediate, conscious memory, and the time required, five to ten seconds, to store an item in long-term memory. Experts differ from novices in science, chess, and other fields that have been studied not only in having more information in permanent memory but also, and more significantly, in being able to process it efficiently. Among experts, for example, items of information are more thoroughly indexed and thus can be rapidly brought to conscious memory. The items, moreover, are elaborately associated or linked with one another. Two consequences of these associations—the ability to recover information by alternative links, even when parts of the direct indexing are lost, and the capacity for extensive means-ends, or trial-and-error, searches—are the essential processes called into play in all problem-solving, from the most elementary scientific discovery to the most advanced.

The increased understanding of these cognitive mechanisms and processes is likely to result in greater efficiencies in memory and thought, and in teaching and learning. An undergraduate of average intelligence, for example, given 230 hours of instruction and practice based on cognitive science, raised his memory for numbers from seven to seventy-nine digits, which is nine times larger than the number taken by psychologists as indicative of superior intelligence.[7] It will be more difficult, of course, to produce such results for higher cognitive processes, such as analysis and synthesis, and to apply their implications in educational practice. Thus human time and concentration are likely to remain essential for learning in the foreseeable future.

The greatest advantage of the expert—and, conversely, the biggest problem for the novice—attempting to gain literacy in cognitively demanding fields is "chunking," the representation of abstract groups of items as linked clusters that can be efficiently processed.[8] Such chunks may underlie mental processes ranging from the childhood stages of cognitive development identified by Jean Piaget, to the themata found by Gerald Holton in the history of scientific discovery.[9] Simon estimates that 50,000 chunks, about the same magni-

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tude as the recognition vocabulary of college-educated readers, may be required for the expert mastery of a special field. The highest achievements in various disciplines, however, may require a memory store of one million chunks, which may take even the talented about seventy hours of concentrated effort per week for a decade to acquire, although seven-to-nine-year-old exceptions such as Mozart and Bobbie Fisher seem to belie this.

The prospect of such prodigious and sustained concentration should impress—if not daunt—the novice, especially in science and mathematics, which are highly specialized and abstracted from ordinary experience. Yet only a small fraction of the total is required for literacy; and only an extra hour or two per day, perhaps taken from the usual several hours that American schoolchildren typically watch television, may enable them to attain levels of achievement far beyond the ordinary in many fields. Children of normal intelligence, moreover, possess the requisite mental mechanisms and processes for respectable attainments; they can acquire scientific literacy and master the information and skills that constitute a small but significant fraction of what the expert commands. The data on achievement test scores of children in other countries compiled in the following section suggest that this fraction can be raised considerably for American adolescents.

INTERNATIONAL COMPARISONS OF SCIENCE ACHIEVEMENT

Although time is an ingredient of learning, it is not in itself a satisfactory index of it; superior opportunity or instruction and more intense motivation can compensate for lower amounts of class and study time in determining the total amount learned. To make valid comparisons of populations or individuals, their learning is better measured directly on standardized, objective achievement tests than indirectly, by indexing the presumed causes of learning.

Objective, or multiple choice, tests themselves are not without controversy. They emphasize, for example, recognition more than recall of the best answer, and students who achieve high scores on such tests are not necessarily able to apply their knowledge in the real world or create new knowledge. Such tests, nonetheless, provide at least a broad, reliable sample of what students know, and without such basic knowledge, or literacy, they cannot be expected to go on to the higher reaches of thought. Most testing authorities in various

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countries agree, moreover, that such tests give a reasonably valid indication of higher mental processes such as understanding and critical thinking.

The best and perhaps only test data that permit reliable international comparisons of science achievement were obtained by the International Association for the Evaluation of Educational Achievement. The data from the international studies are now, unfortunately, a decade old (more recent trends in the United States are discussed in a subsequent section). The studies covered science, literature, reading comprehension, English and French as foreign languages, and civics. Data were collected in 1970-71 on three age groups of students: those about eleven, who were still being taught by a general teacher rather than a subject specialist; those about fourteen, nearly all of whom were still in compulsory school; and those about eighteen, the age corresponding to the terminal year of full-time secondary school in many countries.

Of the nineteen countries that participated in the study, fifteen are developed, while the remaining four are newly industrializing. International cooperation and supervision helped to insure the adequacy of sampling procedures within the countries. Some 300 educators and subject experts planned and executed the data collection, which involved about 10,000 schools, 50,000 teachers, and 285,000 students. Although educational policy-makers in most of the participating countries showed substantial interest in the results, many American policy-makers and educators are only vaguely aware of them.

The science tests covered biology, chemistry, earth science, and physics. The multiple-choice items on the tests assessed functional information, or the practical ability needed for the acquisition of scientific information; comprehension, or the ability to use information acquired from classes, laboratories, and textbooks outside these contexts; application, or the ability to select knowledge and apply it in novel situations; and higher processes, or the recognition, formulation, and solution of problems by experimental methods.

Table 1 shows that the younger children in the fifteen industrialized countries, except Japan, achieved approximately similar scores. At age ten, the average scores of all participating countries were within three points of the grand mean, except for Japan, which was five points above. American youth scored near the grand mean of all industrialized countries at ages ten and fourteen. All countries that had 94 percent or more of their children in school at age fourteen scored within four points of the grand mean, the only exception

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TABLE 1. Average Scores on Science Tests and School Holding Power* at Three Age Levels

	Age 10	Age 14		Age 18	
	Scores	Scores	Holding Power	Scores	Holding Power
Maximum	40	80	100	60	100
Australia	—	25	99	25	29
Belgium (Flemish)	18	21	90	17	47
Belgium (French)	14	15	90	15	47
England	16	21	99	23	20
Federal Republic of Germany	15	24	94	27	9
Finland	17	21	99	20	21
France	—	—	99	18	29
Hungary	17	29	83	23	28
Italy	17	19	55	16	16
Japan	22	31	99	—	70
Netherlands	15	18	98	23	13
New Zealand	—	24	99	29	13
Scotland	14	21	99	23	17
Sweden	18	22	99	19	45
United States	18	22	99	14	75
Mean	17	22	93	21	32
Standard Deviation	8	12		10	

SOURCE: L. C. Comber and John P. Keeves, *Science Education in Nineteen Countries* (New York: John Wiley, 1973), p. 159

*Holding power is the percentage of the age group still in school; nearly all children were still in school at age 10. The dashes indicate populations that some countries elected not to test.

again being Japanese children, who scored nine points higher. Their outstanding performance confirmed the results of the international study of mathematics,[10] and is the subject of analysis later in this essay.

The scores at age eighteen diverged widely by country and are associated with the percentages of students still in school at that age. At one extreme of mass education, the United States, for example, ranked first in 1970-71 percentage of students in school, but last in achievement and achievement gain, from the younger ages to age eighteen. At the other extreme, that of elitism, the Federal Republic of Germany, the Netherlands, and the Commonwealth countries—Australia, England, New Zealand, and Scotland—showed high gains

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in scores from younger to older ages, but each had relatively few eighteen-year-olds in school. Flemish Belgium, Hungary, Finland, and Sweden, and the Romance language countries—France, Italy, and French Belgium—were intermediate between these extremes, with relatively moderate scores and school-holding powers.

Although the Japanese did not test eighteen-year-olds in science, the mathematics study, the science scores of younger students, and other evidence show their divergence from the international trend in having both outstanding test performance and, in 1971, a percentage of older adolescents in school second only to the United States (Japan is now first).[11] Some American and Japanese educators have speculated that Japanese teachers and students rely on memorization of information to achieve high scores. Indeed, Japanese students aged ten and fourteen did score substantially higher on items that require functional information than did students in compulsory school in the other countries. They excel by even greater margins, however, in test subscores tapping understanding, application, and higher processes of science such as hypothesis formulation.

The high scores are partly the result of large amounts of diligent study and instruction. The national guidelines of Japan's Ministry of Education require that 25 percent of the classroom time in lower secondary schools be devoted to science and mathematics, and nearly all students are exposed to this much through ninth grade. In their three years of higher secondary school, nearly all college-bound students (about a third of the total number) take three natural science courses and four mathematics courses, through differential calculus. Direct observations and study of Japanese science classes reveal that the national guidelines are closely followed, that the approved textbooks and equipment are in place, and that little time is wasted on discipline and rote memorization during the long five-and-a-half day school week.[12]

SCIENCE EDUCATION IN THE U.S.S.R.

Although the Soviets have not participated in international surveys, presumably because their ideology denies that students differ from one another on tests, a growing number of scholars in England and the United States have noted that the Soviets have tried to develop science and mathematics courses that surpass those of any other country. Izaak Wirszup of the Department of Mathematics of the University of Chicago first pointed out that, in contrast to the ap-

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proximately half million American students who take a year of calculus in high school or college, 5 million Soviet secondary school students complete a two-year course in the subject. All youth, the Soviets claim, are required to complete five years of physics, four of chemistry, and up to four of biology by the end of secondary school, which nearly all students finish.[13] The avowed purpose of this curriculum is to build up the scientific and technical base of the economy and to supply the military with technologically oriented people.

The U.S. Department of State, the Finniston Report on engineering education in England, and independent scholars have since corroborated the seriousness of Soviet intentions and their widespread attempts to enact the plans.[14] Scholars who have directly observed Soviet classes, however, note that many schools do not have the textbooks and science materials required by the new curriculum, that the preparation of teachers is inadequate and that the teaching is often perfunctory, that students are not exposed to computers and programming, and that they lack motivation and often do not understand the lessons.[15] The best American mathematics students stand up to any in the world, as rankings in the International Mathematics Olympiad show;[16] and that the Soviet Union graduates five times the number of engineers as Japan or the United States hardly makes their consumer products superior. Nonetheless, their intentions should not be underestimated. It would be informative to administer science tests to random samples of Soviet students to determine how effective their bold experiment has been, as well as to study its effects on the well-being of citizens.

SCIENCE EDUCATION IN THE PEOPLE'S REPUBLIC OF CHINA

Until a 1979 visit by the U.S. Science Education Delegation to the People's Republic, led by Paul Hurd of Stanford University, outsiders knew relatively little about the Chinese curriculum. Hurd's comprehensive report[17] makes clear that China has made a massive, centralized effort to upgrade the content and method of science teaching for its 204 million elementary and secondary students. Their national slogan, "Science is the eternal spring," attests to the fact that Chinese leaders view science and technology, along with the other three of the four modernizations—agriculture, industry, and defense—as the key driving forces of economic development and socialistic progress.

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The ten years when the Cultural Revolution held sway (1966-76) took their toll in anti-intellectualism. New policies to combat this and to promote education and science were announced in 1977. Since that time, local and provincial science curricula have been replaced with nationally uniform programs that emphasize demonstrations and experiments by teachers and students, and scientific theories are now related to everyday practices. Mathematics and science courses are required of all full-time students each year; and in 1981 the Ministry of Education proposed to extend both elementary and secondary education for one year, which would result in a twelve-year system, the most ambitious science and mathematics curriculum for schools among the large newly industrializing countries.

Unlike the Soviets, the Chinese acknowledge considerable variation in the nature and nurture of students. The academically talented are sought out and encouraged to attend "key" schools, which have the best teachers and facilities. About 18 percent of Chinese youth now finish secondary school; and only 4 percent of these graduates, increasingly chosen by competitive examinations, go on to university studies. Although qualified teachers are in short supply, self-study, radio, and television courses, as well as specialized schools attached to factories, help diligent students prepare for competitive examinations for university admission. If relative progress among nations in increasing scientific literacy is measured by an index of the number of years students must study science and mathematics multiplied by the number of students, the People's Republic today probably ranks first in the world. (This is not to say, of course, that it compares with Hong Kong or Taiwan in many other indexes of the quality of life.)

Neither the Soviet Union nor the People's Republic—centrally planned, collectivist societies, with laggard economies—provides a useful model for free democracies. What they do provide is a standard of national effort for scientific literacy that must be seriously taken into account by their competitors for world leadership in economic, military, and welfare spheres.

RECENT U.S. SCIENCE ACHIEVEMENT

A careful and comprehensive review of the available U.S. test data shows general declines in the mathematics and science achievement of the nation's youth from the early 1960s through 1971—the year they ranked last in the international study survey of science—to the present time.[18] The average declines are not confined to these sub-

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jects; for example, both the verbal and the mathematics scores on Scholastic Aptitude Tests, taken by about 1.4 million high-school students in recent years, declined about 50 points (or half a standard deviation) from 1965 to 1980. The well-known declines in SATs are attributable, to some extent, to the increasing numbers of less academically able high-school seniors who in earlier decades would have been less likely to apply to college. Other research, however, done by the National Assessment of Educational Progress, which administers tests to representative samples of nine-, thirteen-, and seventeen-year-olds, also shows general and significant declines in science and mathematics achievement during the past decade, although the declines were greatest in the early 1970s and among seventeen-year-old students.

A number of educational and social factors may account for these achievement declines, among them: larger student bodies, and therefore greater competition for educational and career opportunities; disruptive state and federal regulations that were at cross-purposes and interfered with the operation of schools; declines in reading comprehension; the proliferation of minor subjects and nonacademic activities in school curricula; reductions of required courses in the liberal arts and sciences for college admissions; a deemphasis on the mastery of learning skills in schools, homes, and in the society generally; increased amounts of passive watching of intellectually unstimulating television; increased numbers of divorces, single parents, and other changes in families; and social disruption associated with national and local problems and with the war in Vietnam. That these phenomena occurred during the period when scores declined of course neither establishes their weighting nor proves that they were causative factors. Yet the international study and hundreds of educational experiments that specifically link these factors to test achievement (summarized in a subsequent section) corroborate them on the whole, and indicate the more specific psychological determinants of achievement.

EDUCATIONAL IMAGES OF SCIENCE

Before turning to the educational and psychological factors that seem likely to produce substantial improvements in achievement in science and other subjects, the special problem of the image of science and attitudes toward science held by American youth deserves consideration. National survey data collected in recent years give an indication of the seriousness and magnitude of the problem. In 1976

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nine-, thirteen-, and seventeen-year-olds named science least often, in comparison with mathematics, language arts, social studies, and other subjects, as their favorite subject. Students in kindergarten through sixth grade at this time were spending only twenty minutes per day on science lessons, in contrast to eighty-six minutes on average in acquiring basic skills in reading. Although 83 percent of the adult public ranked science as an essential subject for all high-school students in 1979, about 50 percent of the students took no science courses after tenth grade. Furthermore, the percentage of seniors intending to major in college in all sciences and related subjects, such as engineering, declined from 39 percent in 1965 to 19 percent in 1975, and if present trends continue, will decline to a projected 15 percent by 1985.[19]

The data also show that very many teachers feel they are inadequately prepared to teach science and that they are not well supported by school administrations. In 1976 only 22 percent of the elementary schoolteachers felt that they were very well prepared to teach science in contrast to 39 to 63 percent who felt similarly well prepared to teach mathematics, social studies, and reading; and the percentage of those who felt they were not well qualified was from five to ten times higher in science than in the other subjects. About 40 to 60 percent of the science teachers in elementary and secondary schools felt troubled by inadequate facilities, equipment, and supplies, and a third or more believed they did not receive adequate assistance in learning new science teaching methods, obtaining information about instructional materials, implementing inquiry approaches, and in using laboratory equipment and hands-on materials.

Apart from the problem of increasing general literacy among adolescents, science faces several unique difficulties related to motivation, attitudes, and images that help explain the discouraging statistics.[20] In 1957 Margaret Mead and Rhoda Metreaux first noted several negative aspects of the image of scientists.[21] Based on essays about scientists written by a national sample of 35,000 high-school students, Mead and Metreaux drew a composite image of typical scientists. Despite the students' perceptions that scientists are intelligent, dedicated, and serve humanity in important ways, they also believed that the scientist's work "is uninteresting, dull, monotonous, time-consuming. He is so involved in his work that he does not know what is going on in the world. He neglects his family, and has no other intellectual interests, social life, or hobbies. He bores everyone

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except other scientists with incessant talk that no one can understand. No one wants to be such a scientist or to marry him." Whatever the degree of validity of this stereotype, subsequent research shows its pervasiveness among adolescents.[22] Whether ours is the age of narcissistic indulgence in immediate gratification or one of other-directedness, such negative feelings about scientists will hardly inspire students to emulate them; and recent worries about the risk of nuclear catastrophe, with scientists and technologists seen as villains, can hardly improve their image.

Science teachers, moreover, may often make their subject forbidding and academically unrewarding. On average, they give lower grades than other teachers. For example, although students who take physics in high school are about a standard deviation higher in measured intelligence on average than students who do not, their physics grades are generally lower than their grades in other subjects.[23] In one survey, more than two thirds of high-school physics teachers cited student fears for their grade averages and college chances as the first or second most important reason for declining enrollments in physics courses. In a national U.S. sample, the tough grading in high-school physics courses correlated inversely—and strongly (−0.73)—with student interest in continuing the study of physics.[24] These motivational factors, combined with the relaxation of course requirements for university admission and the proliferation of minor subjects offered in high-school curricula, have no doubt contributed to declining scientific literacy in recent decades.

At a time when many colleges and universities are competing to maintain the size of their enrollments, those interested in improving science achievement cannot be unmindful of the risks involved in stiffening their course requirements. Even those with a plentiful supply of high-quality applicants to choose from are not likely to risk changing the diversity of their freshman classes by requiring four years of solid courses in both science and mathematics in high school. However, educational evaluations of the post-*Sputnik* high-school science courses of the 1960s show that several features of curriculum and instruction are feasible and reasonable in increasing science interest and achievement.

SCIENCE CURRICULA

The first generation of these federally funded courses were well suited to students who were to go on as engineering, mathematics,

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and science majors in research universities. Since these courses were not evaluated carefully from the beginning, only later was it realized that many teachers and students were ill prepared for the advanced content. But the second generation of courses, which were designed and evaluated by teams of university scientists, high-school teachers, and psychologists, proved successful not only in the number of students whose achievement was high, but also in encouraging greater interest in continued study in a larger number of students of a great range of abilities.

The Project Physics course developed at Harvard University is a notable example. The Project group added to a history of science highlighting physical discoveries by eminent scientists, a rigorous mathematical explication for advanced students, a series of striking laboratory experiments, and a variety of supplementary course materials to meet the needs and interests of diverse students. They illustrated the links between theories about the physical world during various periods to the philosophical, humanitarian, social, and artistic concerns of the times. Course overviews and guides for both teachers and students provided interesting choices for selecting content and methods of study.

Randomized field trials throughout the United States showed that Project Physics students achieved as well as did other students in other courses, and had significantly more favorable attitudes toward their physics classmates, the subject itself, science and scientists in general, and further formal and informal study of the subject. Other research by the Project group suggests that physics can be made more appealing by showing its artistic, beneficial, humanitarian, and practical aspects and implications. However, the use of field-tested science courses incorporating modern content and superior educational design declined during the 1970s, because school boards interpreted the public demand for going "back to basics" as meaning a return to traditional substance and teaching methods, and because of reduced federal support for course materials and teacher training, tight budgets in local schools, and other educational problems.[25]

EDUCATION RESEARCH

In reacting to current problems and the need for increasing the effectiveness of science education, the National Academy of Sciences, the National Science Teachers Association, the American Association for the Advancement of Science, the National Congress of Parents

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and Teachers, and five other concerned organizations assessed the causes of the present difficulties[26] and gave constructive suggestions for improving the teaching and learning of science. The National Research Council of the NAS, for example, recommended, among other things, the development, evaluation, and revision of new instructional materials for science and mathematics courses, as well as the establishment of teaching resource centers to provide instruction kits, advice, and training to teachers. Ironically, none of these educational and scientific organizations drew explicitly upon the syntheses of educational and psychological research on school learning that had recently been completed.

The funding for research on education is now about $100 million per year, minute compared to that in other areas of science or to the magnitude of the entire educational enterprise. Yet it was recently ranked third in funding priority by the American public, behind only health and energy in a list of thirteen areas of scientific research, including defense, space, weather, and the pursuit of new knowledge about man and nature.[27] In principle, educational research resembles investigation in agriculture, industry, medicine, and other applied fields in that (1) valuable effects are identified and measured; (2) their plausible causes are hypothesized; (3) the empirical relations of causes and effects are tested; (4) the results from replicated studies are compiled; (5) causes that produce good results, without harmful side effects, are adopted in practice. There are now sufficient data from research on factors in school learning, collected over several decades, for compilations and statistical syntheses, and these have been carried out by groups at Harvard, Stanford, and the universities of Illinois (Chicago), Michigan, and Colorado.[28]

Syntheses of educational research indicate that no single study, no matter how large or widely publicized, can be taken by itself as definitive. The imprecision of educational measurements and experimental controls require the evaluation and averaging of results of many studies in order to draw valid conclusions. Yet syntheses do show that a fairly limited number of factors are potent, consistent, and widely generalizable to various school subjects, educational conditions, and student characteristics.

The factors that promote learning can be divided into several dozen subcategories, but it is useful for our present purposes to discuss eight major categories and the estimated percentages of variance in school learning outcomes that are statistically accounted for on average by each: student ability (45 percent); student motivation (9 per-

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cent); amount of instruction, including self-instruction (16 percent); quality of instruction, also including self-instruction (27 percent); the psychological climate of the classroom group (36 percent); educational stimulation and support by adults in the home (16 percent); academic characteristics of the student's peer group outside school (6 percent); and amount of exposure to the usual commercial television (5 percent)—which is negatively associated with school learning on average. The percentages add up to more than 100 percent because the categories are statistically colinear, that is, students who are advantaged in one are likely to be so in the others.

Student ability and motivation and the amount and quality of instruction all appear to be necessary for learning; without at least a minimum level of each, the student can learn very little. Large amounts of instruction and high degrees of ability, for example, may count for little in learning if motivation is absent or the instruction is unsuitable.

The last four categories—psychological climate of the class, stimulation and support from the home, peer group with high academic interests and goals, and minimum exposure to the usual television programs—include indirect factors that increase abilities, incentives, and opportunities that in turn raise the efficiency of learning both inside and outside school. There are certainly other social and economic factors that bear on learning in school, but they are less proximate and tangible and have not been strongly and consistently linked to school learning. Other educational factors, moreover, such as class size, expenditures per student, and private governance (independent or sectarian, as opposed to public control of schools) appear to be comparatively weak and inconsistent correlates of learning, especially if the initial abilities of students are taken into consideration. Thus direct improvements in the eight essential, proximate factors hold the best hope for improving literacy in general, but the necessary changes will require rethinking conventional educational organizations and procedures.

In economically depressed urban areas, for example, which have some of the lowest levels of general and scientific literacy, school-coordinated educational interventions in the home have been remarkably successful in improving achievement. Programs in which school staff organize cooperative study groups for parents, and provide instructional materials and procedures for use with their children, nearly always prove effective in developing a student's ability

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and in raising motivation and achievement scores in the usual school subjects.[29] Nearly all of the fifty-three field trials demonstrate the effectiveness of such programs in raising test scores in reading, science, mathematics, and other subjects. These evaluations further suggest that the learning gap between middle-class and poor children might be considerably reduced if such programs were sustained during the school years.

Synthesis of research on the amount of television viewing at home, moreover, suggests that achievement would be raised considerably if homework and other educative activities were substituted for several of the average three to seven hours of television watched each day in typical American households,[30] although the potential for good programs such as "Nova," which show science and scientists at work, should not be overlooked. Since parents are responsible for supervising about 85 percent of the potentially educative time for the first eighteen years of their children's lives—that is, the waking hours the children are not in school—even moderate improvements in parents' effectiveness in encouraging their children, and in supervising and discussing their television viewing, seem likely to bring about substantial long-term effects on literacy.

Instruction in school, however, can also be made much more effective; the quality of the 180 six-hour days, which add up to 12,960 hours over twelve school years, might double or triple without increase in the time itself. The major problem of ordinary instruction—which includes recitation, lecture, discussion, films, seatwork, and laboratory sessions—is suiting the content, pace, and difficulty of the lesson to each child individually; aiming toward the middle third, for example, may mean that two thirds of the class are either incapable of learning or already knowledgeable. Children in all countries differ widely in ability and achievement in first grade, and they grow steadily more diverse during the subsequent years. The problem is particularly challenging in the United States because of our national commitment to mass education. Moreover, unlike many other nations where decisions are made by ministries of education, subject matter is mainly decided within local school districts and therefore varies widely. Since the U.S. population is highly mobile—according to the Census Bureau, 45 percent changed residence between 1975 and 1980—we see the results of such local decision-making in the highly varied patterns of individual ability and knowledge, even in a single class.

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PROVEN EDUCATIONAL TECHNIQUES

Several innovations have increased the effectiveness of instruction for diverse as well as more uniform student groups.[31] The first, developed at the University of Chicago and called "mastery learning," breaks the subject into small, usually written units. This approach allows each student to work through these units individually at his or her own pace; requires near-perfect mastery on tests over one unit before proceeding to the next; and provides more time, several alternative means of learning, and corrective feedback to students who encounter difficulties. The mastery approach has been used most frequently in elementary aspects of various school subjects, but it is also used in secondary and college mathematics and science courses, perhaps because greater agreement can be reached on which parts of the subject are most important to learn.

A second approach, called "team-games tournaments," resembles the "quality circles" of Japanese industry in harnessing the social forces of competition and cooperation. Developed by groups at Johns Hopkins and the University of Minnesota, the approach calls for students, in teams of from five to seven members, to cooperate with one another in competition with other teams within or outside the school. The teacher, in effect, delegates to each team the responsibility for the organization and means of learning units of the subject. To encourage their productive cooperation, the teams may be deliberately composed of students of different ability, age, sex, and ethnicity. The grades, marks, or ranks given to team members can be chosen to depend on their individual performances or that of the best, average, or worst scoring team member so as to enhance the team skills and values required in adult life, in which the competence of the best, average, or weakest member of work groups must be raised.

Another approach, initially developed by primary schoolteachers in England, Boston, New York City, and North Dakota, is called "open education" because it encourages open-ended inquiry; it is alternatively called "the integrated day" because it integrates rather than separates the usual school subjects. The teacher and students jointly plan the purposes, methods, and evaluation of extensive projects—for example, an analysis of local neighborhood traffic problems—which could require the development and application of skills in mathematics, science, civics, library research, and writing. Open education is an attempt to avoid overreliance on the authority of the teacher and textbooks, and to provide genuine opportunities for

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students to formulate educational alternatives rather than choose among them or face only one. Students in open programs often carry out significant original work in surprising depth; they score slightly-to-moderately higher on psychological measures of creativity, independence, problem-solving, and educational motivation; and their reports demonstrate the capacity to conduct sustained inquiry. If scientific literacy includes more than basic knowledge and skills of communication—for example, appreciation of scientific methods and the ability to investigate original sources and materials—then open education would have a useful role in its improvement.

COMPUTER-AIDED EDUCATION

Continuing refinement and more widespread use of mastery, team, and open approaches could substantially raise literacy and interest in science and other school subjects. The computer, however, has the potential to revolutionize mass education. It may prove comparable to movable type and the public school in extending literacy and developing human capital. As Herbert Simon points out, its impact may be as significant as several of the great scientific ideas of the last millennium:

> The definition of man's uniqueness has always formed the kernel of his cosmological and ethical systems. With Copernicus and Galileo, he ceased to be the species located at the center of the universe, attended by sun and stars. With Darwin, he ceased to be the species created and specially endowed by God with soul and reason. With Freud, he ceased to be the species whose behavior was potentially governable by rational mind. As we begin to produce mechanisms that think and learn, he has ceased to be the species uniquely capable of complex, intelligent manipulation of his environment.[32]

But computers can not only think and learn, but react and teach.

The first phase of research on computer-assisted instruction, much of it concentrated in science and mathematics, shows that the computer can effectively supplement or supplant traditional teaching. This work, however, mainly adopted recitation and question-and-answer methods, and made little use of currently feasible technologies, such as compacting the information of a library into a home file cabinet; providing rapid scanning, compilation, and visual displays of data; simulating natural and human events; diagnosing and remedying the particular problems of individual students; enabling them to browse and follow their own interests and talents; connecting

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them by satellite with distant teachers, interest groups, and databanks; maintaining profiles of interests and accomplishments of students to serve as a basis for planning tailor-made curricula; and even incorporating into educational programs a desirable amount of capriciousness and serendipity.

Computers are becoming cheaper, more responsive, and easier to use. Within a decade, they will be common in homes, and will offer unparalleled challenges and opportunities to educators, parents, and students. Just as Arabic numerals, place value, and cheap electronic calculators enabled convenient, accurate calculation, computers, because of their increasing cost-effectiveness and capacity to manipulate symbols and ideas, will serve as ready instructors and colleagues. For those who have not mastered abstruse concepts and topics, the computer can also serve as mental prosthesis, or kindly guide, in processing information and ideas. The fascinating part of the story of computers in education will be told during the remainder of this century.

FUNDING PROBLEMS

Educational research provides reasonable hope that the effectiveness of our schools can be substantially increased, both in general and in the special cases of science and mathematics, by employing more widely and intensely the productive innovations discussed above. It might be accomplished massively and swiftly, incrementally and piecemeal, or not at all. The initiative and funds for mounting a large effort may be lacking, and if so, the outlook for education and science literacy will hardly be bright. The National Science Foundation has disbanded the Science Education Directorate and plans to grant no new funds for educational research and development. The Reagan Administration proposes to abolish the newly created Department of Education and instead will leave to the states, through their allocations of block grant funds, decisions regarding how much money will go to education and in what areas. Federal, state, and local governments, and educational agencies are tightly budgeted; many are spending more than their incomes and may have to curtail educational services severely. Thus a range of statist, efficient, and free-market solutions that might have seemed improbable in the past may have to be seriously considered in the next several years.

The president and Congress, for example, in response to future reports by federal commissions on science education and on educa-

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tional excellence, and by other groups now appointed and in deliberation, might declare a national educational emergency, and allocate several billions of dollars to upgrade education generally and raise the salaries of mathematics and science teachers to make them more competitive with salaries in private industry. A related possibility, already begun in California and North Carolina, is that state governments will authorize and allocate funds for special equipment, programs, and schools for science, mathematics, and computer science. Private corporations have already begun contributing to such efforts.

Another possibility is to increase class size. Education research shows that variations in class size, especially above fifteen students, make little difference in learning. Thus, using the same amount of funds, the salaries for a retrained and more elite teaching force could be doubled and lower-paid classroom aides and laborsaving technology more widely used.

A CASE STUDY OF JAPAN

The scientific literacy of American students has declined, and we have before us the means of raising achievement-test performance in science, mathematics, and other subjects. The questions remain: *Should* we raise the scores? What mental qualities would this foster? And what economic and noneconomic good would be served? Japan—a democracy that has chosen to invest heavily in human capital, particularly in excellence in mass education—provides an interesting case in point, and if not a model to emulate, then a standard to aim for or exceed.

In *Daedalus* a decade and a half ago, Herman Kahn and Anthony Wiener identified Japan, along with the United States and Western Europe, as an advanced mass-consumption society entering the post-industrial stage. Despite Japan's relative poverty earlier in the century, and its lack of physical resources, it was forecast that Japan would continue its rapid economic advance and surpass the United States in per capita income by 1990. Actually, because of wide fluctuations in exchange rates, Japan did just this in 1978, and if present trends continue, will do so decisively in the mid-1980s.[33] Japan's unprecedented postwar economic growth accompanied a sharp rise in average IQ from 103 to 111. Recent British research shows that currently about five times as many Japanese as Americans and Western Europeans reach superior IQ levels, and 77 percent of them ex-

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ceed the mean of about 100 in Western countries, a mean that has remained stable since World War II. Since heredity cannot determine large changes over short time periods, the change is most certainly attributable to social environment, family circumstances, education, health, and other human-capital investments and enhancements.[34]

Nor have such gains been made at the expense of the development of other talents and accomplishments, even civilities. Japanese students lead the world in the mastery of musical instruments and foreign languages and in the rate of high-school completion. Japan ranks first in number of patents granted and novels published, in life expectancy and in public safety. The quality of goods and services in such industries as transportation, communication, consumer products, and electronics is among the best.[35] In addition, at Tsukuba Science City, under construction at a cost of $15 billion, and elsewhere, Japan is establishing the material and human resources necessary to become the world leader in the production of carbon and optical fibers, engineering plastics, compound semiconductors, industrial robots, telecommunications, biotechnology, and other high technologies.[36] A walk through a department store on the Ginza, a ride on the bullet train to Kyoto, a night in a country inn, and an inquiry of a stranger about directions in Tokyo will be illuminating to those who—remembering the immediate postwar years or photographs of crowded subways or polluting factories—think Japan has put aside the less objectifiable of the traditional or modern amenities.

Japan's intentions to make Tokyo the information capital of the world and to develop fifth-generation computers that can listen, speak, and exercise perception and intelligence continues a centuries-old tradition of importing and adapting knowledge and techniques, starting with Buddhism and Confucianism from China and Korea. During the Meiji restoration a century ago, Japan first sought to infuse both Western technology and the spirit of capitalism into their country; the emperor himself declared that intellect and learning would be sought from throughout the world. Hundreds of industrial experts and ordinary technicians, called "live machines," perhaps in appreciation of their human-capital value, were temporarily imported from England—then the premier industrial power—France, Germany, and the United States, to set up enterprises and techniques, which were then improved and more widely adapted. By 1868 the literacy rate was comparable to Disraeli's England, and in 1872, a decade before England, Japan made elementary school education compulsory, without regard to sex and social class. The government

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and legal, corporate, and religious bureaucracies and overhead were kept lean; and the small amounts of taxes collected went not for redistribution, but for roads, harbors, irrigation, other productive investments, and model factories that were later sold off to encourage private entrepreneurship.[37]

After World War II, Japan again reinvested and redeployed human resources. Secondary education was made compulsory, and educational standards were raised. In 1949, 30 percent of governmental workers were laid off, and large private firms dismissed even greater percentages of their employees. Bankruptcies rose to record levels in the 1970s, to twice the rate of the United States; older, less internationally competitive factories and industries were allowed to die, and highly technological ones took their place. The Japanese government proposes to sell the national railroad and airline, perhaps the best in the world, to provide further entrepreneurial and market efficiency. From a per capita income base of $188 in 1953—less than that of Brazil and Malaysia—Japan grew faster in industrial productivity and real GNP than any other major country, while maintaining low rates of unemployment and income inequality.[38] If present trends continue, Japan's per capita income will be twice that of the United States within a decade or two.[39] Since Japan lacked valuable minerals, arable land, and until recently, financial resources, its unprecedented success must in large part be attributable to investments in human knowledge and skills and imported and improved Western technology.

LITERACY AND ECONOMIC PRODUCTIVITY

An increasing store of valuable knowledge requires that the common men and women of nations that intend to be internationally competitive in world markets and to increase their material well-being, must possess a high standard of literacy, especially scientific, quantitative, and technical literacy. The United States, however, is declining in scientific literacy, and for the period 1960-80, exceeded only England and Italy in economic performance in a list that included Canada, Japan, and the major countries of Western Europe.[40] In 1965 General Motors earned twice as much as the combined totals of the top thirty German and top thirty Japanese industrial companies; in 1980 GM reported its first deficit since the Great Depression, and in 1982 announced that it would import and sell Japanese cars. From 1965 to 1980, the U.S. share of companies with world sales

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over $1 billion declined from 70 to 40 percent. From 1870 to 1950, while American education and literacy expanded, GNP per worker grew only 0.7 percent faster than that of Europe as a whole, but it was sufficient to place the United States first in the world in economic growth and per capita income. Yet for the postwar period, the productivity growth of Japan and West Germany exceeded ours by 3 to 6 percent.[41]

The recent superior performance of other countries is of course partly attributable to their faster growth from a smaller, devastated industrial base after the war. Economists agree, however, that there is more to the story: the two most comprehensive analyses suggest that an estimated 67 percent of the productivity growth in the United States from 1948 to 1973 was attributable to advances in applied knowledge, technology, and in the education and experience of the labor force.[42] A country's past accomplishments and current investments in high science, however, seem relatively unimportant to such growth, since science is by definition public knowledge that can be adapted by other countries (Japan and the Soviet Union are notable examples), and since decades of effort, great sums of money, and high risks are required to translate science into marketable services and products. Nor are total research and development appropriations or private industrial funds for nonmilitary and nonspace-related research and development vital; the United Kingdom and the United States, the productivity-growth laggards, spend more on both as percentages of GNP than Japan and West Germany, the leaders.[43]

Although scientific and engineering breakthroughs occasionally raise productivity dramatically, progress comes mainly from adaption of scientific and technological ideas, some of them quite old; small, incremental improvements in services, manufacturing procedures, and materials; redesign or substitution of activities, components, and products; reductions in costs; steady advances in performance, quality, style, and consumer appeals; and intelligent attention to details by the work force. To discover, plan, implement, and measure the results of such changes in traditional or high technology requires manufacturing, service, and sales forces that are knowledgeable and motivated; it requires not necessarily superior scientists, engineers, and managers, but educated workers who are skilled with materials, technology, and quantitative data; who can absorb and propagate applied science; and who can communicate and cooperate with one another for the individual as well as the corporate and national good.[44]

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Education, of course, enlarges both theoretical and applied knowledge, as well as the capacity and motivation to acquire more of it. Recent evidence shows that education also raises personal productivity. Although the evidence is hardly certain, it is plausible and consistent, and its implications should not be ignored. Case studies, for example, show that doctors who are better and more recently educated are the earliest adopters of new pharmaceuticals, and that better-educated farmers acquire more efficient technologies more rapidly.[45] Nearly all studies of various professions and occupations show that school, college, and professional school grade point averages positively predict occupation-success indicators such as earnings and supervisor and peer-effectiveness ratings;[46] and the predictions are stronger and remain positive when the quality of the institution granting the grades and other factors are taken into account.[47] Workers with higher educational attainments, moreover, often gravitate to firms employing new technology, are quick to learn by doing, and can shift flexibly from one complex task to another.[48]

Even if what is learned in school and college is considered superficial verbal competence, it predicts income—a partial indicator of what the individual's pecuniary worth to society will be, as well as the quality of life an individual can expect to have. The only U.S. national study that provides direct evidence on the weighting of several factors showed that a short general vocabulary test provided a better prediction of adult income than did years of education and parental social class; and verbal competence thus measured remained the only significant predictor among the three when they were simultaneously controlled for one another.[49]

If the term "scientific literacy" includes the social sciences and the application of scientific teamwork in solving problems, improved scientific education and technological training can further contribute to economic well-being. Japanese "quality circles"—which use statistical procedures, graphics, and group discussion to identify defects in products, procedures, and services, as well as employ generally the minds and hearts and hands of workers to improve productivity—are traceable to long-standing views of American psychologists such as Chris Argyris, Kurt Lewin, Rensis Likert, and Douglas McGregor. The United States, however, may have to reacquire the concrete skills of applying such participatory techniques from the Japanese; for example, three years after Matsushita (Panasonic) bought Motorola's television assembly plant in Franklin Park, Illinois, production, with essentially the same equipment but with reeducated American man-

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agers and workers, increased 30 percent; more important, defects fell from 150 to less than 4 per hundred sets.[50]

* * *

The United States still leads the world in total national wealth, economic productivity, and scientific discovery, but it is falling behind other countries in per capita income, growth in productivity and other economic criteria, and in indexes of the quality of modern life, goods, and services. Increasing the effectiveness of the schools with respect to English, foreign languages, civics, history, mathematics, and science, and especially with respect to scientific and technical literacy, by employing the methods suggested by educational research that I have discussed, should be a part of a long-term solution to the problems before us.

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Jon D. Miller

Scientific Literacy: A Conceptual and Empirical Review

IN A DEMOCRATIC SOCIETY, the level of scientific literacy in the population has important implications for science policy decisions. As this essay will show, the level of scientific literacy in the United States is deplorably low; thus any measures we can take to raise this level, to foster informed and intelligent participation in science policy issues, will improve the quality of both our science and technology and our political life.

In order to provide a framework for a discussion of scientific literacy in the United States, it is necessary first to examine how the meaning of the term itself has changed, to look at some of the attempts to measure it, and to ascertain which groups are scientifically literate and what levels of literacy have been attained.

EVOLUTION OF MEANING

"Scientific literacy" is one of those terms that is often used but seldom defined. To be literate has two quite different meanings: to be learned, and—perhaps what most people today mean when they speak of literacy or of being literate—to be able to read and write. Unfortunately, a good deal of the current debate about scientific literacy fails to distinguish between the two, and much of the confusion surrounding the issue can be traced to this omission.

Can a person with a thorough grounding in the traditional study of letters, but lacking at least some knowledge of science—and vice versa—be considered learned? This question has been the subject of a healthy (though sporadic) debate over the last century. Thomas Huxley began it, in 1880, with his lecture "Science and Culture," and

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Matthew Arnold responded in 1882 with "Literature and Science." C.P. Snow took up the argument again in 1959 in *The Two Cultures,* to be answered by F.R. Leavis in 1962 in *Two Cultures? The Significance of C.P. Snow.* The debate was joined by Lionel Trilling, Martin Green, Richard Wollheim, and others.[1] Yet, all of these contributions had as their focus the definition of being learned, not the issue of communicating science to broader populations, although Harry Levin in 1965 characterized Snow's lecture as an "earnest plea for intercommunication across the high table, as between exponents of the scientific and humanistic disciplines."[2]

Although the issues raised by Huxley, Arnold, and Snow have lost none of their importance, they are generally beyond the scope of this essay. In one significant sense, however, Huxley and Snow, who called for the incorporation of formal science training into the collegiate programs of Cambridge, won a de facto victory. Graduate education generally remains specialized, but the inclusion of both the humanities and the sciences into the undergraduate curriculum of arts and sciences colleges is now almost universal in the United States and Western Europe. On the other hand, numerous technical institutes and engineering colleges have largely excluded the study of both the humanities and the social sciences from the undergraduate core curriculum.

The second meaning of literate—to be able to read and write at a functional level—can be extended to suggest that scientific literacy refers to the ability of the individual to read about, comprehend, and express an opinion on scientific matters.

The development of scientific literacy by a broader public did not become the subject of systematic study until the 1930s, when John Dewey, in a paper entitled "The Supreme Intellectual Obligation," declared that

> the responsibility of science cannot be fulfilled by methods that are chiefly concerned with self-perpetuation of specialized science to the neglect of influencing the much larger number to adopt into the very make-up of their minds those attitudes of openmindedness, intellectual integrity, observation, and interest in testing their opinions and beliefs, that are characteristic of the scientific attitude.[3]

Following Dewey's charge, a number of science educators began to think about the formal definition and measurement of the scientific attitude. Ira C. Davis, for one, believed that the individual who possesses this attitude will "show a willingness to change his opinion on the basis of new evidence; . . . search for the whole truth without

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prejudice; . . . have a concept of cause and effect relationships; . . . make a habit of basing judgment on fact; and . . . have the ability to distinguish between fact and theory."[4] Victor H. Noll and A.G. Hoff came up with similar definitions, and they began the task of developing items for use in testing.[5] Virtually all of the empirical work done before the Second World War had as its focus the development of a scientific attitude.

With the postwar growth of standardized testing, a number of science educators and test developers began to focus on the level of comprehension of basic scientific constructs and terms. A growing number of studies, epitomized by the standardized tests of the Educational Testing Service (ETS) and the College Board, attempted to chart the level of cognitive scientific knowledge among various groups in the population.

Beginning in the mid-sixties, the National Assessment of Educational Progress (NAEP) started to collect data from national random samples of precollegiate students concerning, among other categories, their level of scientific knowledge. These studies were the first to measure systematically both the understanding of the norms, or processes, of science and the cognitive content of the major disciplines. These two dimensions together—an understanding of the norms of science and knowledge of major scientific constructs—constitute the traditional meaning of scientific literacy as applied to broader populations. But if scientific literacy is to become truly relevant to our contemporary situation, one additional dimension must be added: awareness of the impact of science and technology on society and the policy choices that must inevitably emerge.

About fifteen years ago, concern about the public's knowledge of various scientific or technological public policy issues began to surface. Environmental groups, for example, found that some minimal level of scientific knowledge was necessary if individuals were to understand debates about pollution of the environment. In addition, the increasing number of state referenda on issues such as nuclear power and laetrile were generating apprehension in the scientific community about the public's ability to understand the issues and to make an informed judgment. These concerns echo those of the fifties, when groups opposed to fluoridation of water were able to win referenda on this issue, primarily because the majority of those voting were not scientifically literate. Not able to comprehend the arguments about fluoridation, many voters appeared to prefer not to drink something whose potential effects they did not understand.

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In summarizing the case for a broader public understanding of public policy issues—what Benjamin Shen has recently characterized as "civic science literacy"[6]—Robert Morison wrote:

> Science can no longer be content to present itself as an activity independent of the rest of society, governed by its own rules and directed by the inner dynamics of its own processes. Too many of these processes have effects which, though beneficial in many respects, often strike the average man as a threat to his autonomy. Too often science seems to be thrusting society as a whole in directions in which it does not fully understand and which it certainly has not chosen.
>
> The scientific community must redouble its efforts to present science—in the classroom, in the public press, and through education-extension activities of various kinds—as a fully understandable process, "justifiable to man," and controllable by him.[7]

SOME PREVIOUS EMPIRICAL MEASURES

Despite the lively discourse that surrounded the issue of scientific literacy, few efforts were made to measure it for the population broadly, or even for major segments of it. Until the last decade, nearly all the important efforts that were made focused on school populations, most often on small selected sets of schools or classrooms. For a nation generally disposed to social measurement, this was a somewhat disappointing database.

Before analyzing its current levels and distribution, it might be useful to review briefly the previous efforts made to measure scientific literacy from the perspective of its three constitutive dimensions.

The Norms and Methods of Science

Most of the early empirical work in this area had as its focus the definition and measurement of the scientific attitude as described by Dewey. Davis, using examples from the everyday experience of the student, sought to develop sets of items that would create situations to force a judgment. By providing a set of rational, intuitive, or superstitious alternatives, Davis attempted to measure the student's utilization of the scientific attitude. For example, students were presented with statements such as "Red hair means that a person has a fiery temperament," "A disease is a punishment for some particular moral wrong," or "Air is composed of molecules." Davis collected data from approximately one thousand Wisconsin high-school students and teachers, and reached the following conclusions:

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1. High-school pupils in Wisconsin are not superstitious.

2. High-school pupils make almost as good records as the teachers.

3. Many of the theories in science are being taught as facts by many of our best teachers.

4. Pupils seem to have a fairly clear concept of the cause and effect relationship, but they do not seem to be able to recognize the adequacy of a supposed cause to produce the given result.

5. Many teachers tend to propagandize their material when there is no scientific evidence for the statements they make.

6. Teachers do not consciously attempt to develop the characteristics of a scientific attitude. If pupils have acquired these characteristics, it has come about by some process of thinking or experiences outside of the science classroom.[8]

Tests similar to those used by Davis, stressing the use of everyday examples to measure the use of scientific thinking, were developed by Noll and Hoff.[9]

In its science testing program, NAEP included a number of items concerning knowledge of scientific norms and the ability to reason to conclusions from relatively simple data. These studies provide the only national estimates of the knowledge levels of scientific norms or the ability of young people to think in logical and ordered terms.

In its 1972-73 assessment of science achievement, students of nine, thirteen, and seventeen years of age were asked to perform a set of simple tests and experiments and to explain the results. Each student, for example, was shown unlabeled pieces of sandstone, quartz, and granite, and asked to select the stone that would "most likely [be] formed under water." The sandstone was selected by 60 percent of the nine-year-olds, 71 percent of the thirteen-year-olds, and 78 percent of the seventeen-year-olds. When asked to explain why they had selected the sandstone, however, only 7 percent of the first group, 15 percent of the second, and 26 percent of the third were able to describe the process of sedimentation, even vaguely, or to provide other acceptable explanations.[10] That similar patterns were found in several other experiments, such as color mixing, temperature mixing, relative volume, rotation and revolution, and simple circuit boards, suggests that much of what may appear to be scientific knowledge in multiple-choice testing is not supported by an *understanding* of the underlying scientific principles and processes.

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Unfortunately, the National Assessment did not use multi-item scales extensively, which would have provided more reliable summary measures, preferring instead to collect and report sets of individual test items from year to year. Most of these data are available for secondary analysis, and there is much work to be done in converting this very important archive into analyses to provide a portrait of the level and distribution of precollegiate and young adult understanding of the norms and methods of science.[11]

Cognitive Science Knowledge

As the use of standardized testing expanded during the fifties and sixties, a number of tests were developed to measure a student's knowledge of basic scientific constructs.[12] A majority were used by teachers and school systems to evaluate individual students, to determine admission or placement, or for related academic counseling purposes. While some test score summaries have been published by the ETS and other national testing services, these reports reflect the scores of only those students who plan to attend college or who for some other reason have elected to take the test; and it is this self-selected nature of the student populations involved that continues to raise substantial problems for interpretation and analysis. (The NAEP studies cited previously are noteworthy in that they are the only national data collection program in which the bias of self-selection inherent in voluntary testing programs has been eliminated.)

The only national data set that provides scores of cognitive science knowledge for broad and randomly selected populations is the National Assessment, which for over a decade has periodically collected cognitive science knowledge data from national samples of nine-, thirteen-, and seventeen-year-olds. In some years, a national sample of young adults twenty-six through thirty-five was also used to assess the continuing impact of formal study.

On the basis of three assessments between 1969 and 1977, NAEP found declining science achievement scores for all age groups and almost all socioeconomic subgroups. Female students, black students, students whose parents did not complete high school, and students who live in large central cities were all substantially below the national average in science achievement.[13]

Attitudes toward Organized Science

The third dimension of the scientific literacy typology is an individual's knowledge about what may be generally called organized sci-

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ence—that is, basic science, applied science, and development—and includes both general information about the impact of science on the individual and society and more concrete policy information on specific scientific or technological issues.

The first national study that included a meaningful set of measures of attitudes toward organized science and knowledge about it was a 1957 science news survey conducted by the Survey Research Center at the University of Michigan for the National Association of Science Writers. Although the purpose of the survey was to study the public's interest in science news and its information consumption patterns, the interview schedule also included measures of general attitudes toward organized science and knowledge of it, as well as some issues that were then current.[14]

The survey found that only a minority of the public was strongly interested in scientific issues and that the level of public knowledge about science was relatively low. It found, too, that the public tended to hold high expectations for the future achievements of science and technology, but were aware of the two-edged nature of the scientific enterprise. Stephen Withey summarized the public mood: "On the surface the natives are quiet, supportive, and appreciative but there is some questioning, some alert watching, and considerable mistrust. The public will wait and see; they have no reason to do anything else, and many have no other place to turn."[15]

Beginning in 1972, the National Science Board initiated a biennial survey of public attitudes toward science and technology,[16] which found that the public retained a high level of appreciation and expectation amid signs of an increasing wariness. Yet, there was no evidence to indicate the development of a strong antiscience sentiment.

In subsequent surveys in 1979 and 1981, the focus changed to a more structured approach, in an attempt to identify the segment of the population interested in, and knowledgeable about, science policy matters, and to examine the attitudes of this "attentive public."[17] The results showed that about 20 percent of American adults followed scientific matters regularly and that their attitude toward organized science was more favorable as a rule than that of the general population groups previously measured.

The attitudes of young adults toward organized science was even more positive. In a 1978 national survey of high-school and college students, researchers identified the developmental roots of adult attentiveness to science matters, and determined that the attitudes of these young adults were generally positive and supportive of sci-

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ence.[18] Like older Americans surveyed, however, substantial segments of these young adults were not very interested in, and had little information about, scientific and technological matters. Approximately 90 percent of the high-school students who did not plan to attend college failed to meet minimal criteria for interest in scientific issues or for cognitive knowledge of basic scientific constructs. There is no reason to believe that the next generation will be antiscientific; more likely, it will continue to hold the same attitudes—corrected for the rising levels of educational achievement of the new generation—as do adults today.

That there has been little consensus on a comprehensive definition of scientific literacy seems obvious from the relatively uncoordinated efforts to measure its dimensions. And although a number of partial measures have been developed, we are still without one that will help delineate that segment of the American population that we can call scientifically literate. It is to the task of constructing and analyzing a single measure of scientific literacy that we now turn.

LEVELS AND DISTRIBUTION OF SCIENTIFIC LITERACY

The 1979 National Science Foundation survey of adult attitudes toward science and technology, on which the following examination of the current level of scientific literacy and its distribution in the population is based, included all of the items necessary to measure each of the three dimensions of scientific literacy, and utilized a national probability sample from which valid generalizations can be made.[19] We will look first at the public's ability to understand the process of scientific study, then at their comprehension of selected disciplinary constructs, and finally, examine the public's understanding of some contemporary political issues that involve science and technology. Once each of the dimensions has been measured appropriately, the three facets will be combined into a single measure of scientific literacy.

Understanding the Scientific Approach

The first national survey to measure adult comprehension (as opposed to that of schoolchildren and young adults) of the process of scientific study—what Dewey termed the scientific attitude—was the University of Michigan science news study of 1957. Each respondent was asked to define the meaning of "scientific study," and the open-ended response was coded into a set of categories that reflected vari-

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ous perceptions of scientific study. In reviewing the data, Withey concluded that only about 12 percent could be said to have a reasonable understanding of the term.[20]

The NSF survey included the same question: it asked each respondent to assess whether he or she had a clear understanding of the meaning of scientific study, a general sense of its meaning, or little understanding of its meaning. Those who said they had a clear understanding of the term were asked to explain its meaning in their own words, and the response was recorded verbatim.[21] (The responses were later coded by two coders independently, and those cases that involved disagreements in coding were judged by the coding supervisor.)

Approximately 14 percent of those surveyed were able to provide a minimally acceptable definition[22] of the meaning of scientific study (Table 1), a level of understanding that is not statistically different from the 12 percent previously recorded. There has apparently been little improvement over the last twenty-two years in the proportion of American adults who correctly understand the meaning of scientific study.

Following the multiple measurement principle,[23] the 1979 survey also included a short battery of items about astrology. Each respondent was asked, first, how often he or she read astrology reports, and then to characterize astrology as very, "sort of," or not at all scientific. Eight percent thought astrology was very scientific; 34 said it

TABLE 1. Adults Who Understand the Scientific Approach

	%	N
All adults	9	1,635
Age		
17-34	14	670
35-54	8	492
55 and over	4	473
Gender		
Female	8	862
Male	11	773
Education		
Less than high school	1	465
High-school degree	5	550
Some college	16	382
Baccalaureate degree	24	146
Graduate degree	32	92

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was sort of scientific; and half recognized that it is not scientific at all. In general, these responses allowed correction of the results obtained from the question about the meaning of scientific study, because any person who correctly understood the scientific process would have rejected the notion of astrology as scientific. Following this logic, a final measure of understanding of scientific study was constructed: to qualify as understanding the process of scientific investigation, a respondent would have to be able to provide a reasonable definition of scientific study *and* to recognize that astrology is not scientific. Using this yardstick, only 9 percent of those sampled could meet this rather minimal test.

The 1979 data pointed to a strong association between formal education and an understanding of the scientific approach, yet only a third of those with graduate degrees qualified as understanding the process of scientific inquiry. A separate multivariate logit analysis indicated that most of the differences observed by age and gender could be attributed to the level of formal education.

From these data, only one in ten American adults, it appears, understands the meaning of the scientific approach, but other data from the same survey suggest that the majority of the public *can* differentiate between science and pseudoscience in more concrete terms. When asked if the results of animal studies on the safety and efficacy of chemical food additives had induced them to change their eating or food buying habits, 74 percent of the respondents answered in the affirmative, compared to 5 percent who said that astrology reports had prompted them at one time or another to change their plans. As Table 2 shows, although the influence of astrology reports on behavior was significantly associated with low levels of formal education, there was a uniformly high acceptance of the results of animal studies regardless of the level of educational attainment.

In 1979, then, only one in ten American adults understood the meaning of the scientific approach, but a substantially larger proportion of the population did have a high level of confidence—or faith—in what they perceived to be scientific studies.

Understanding Basic Scientific Constructs

The argument here is clear and simple. The individual who does not comprehend basic terms like atom, molecule, cell, gravity, or radiation will find it nearly impossible to follow the public discussion of scientific results or public policy issues pertaining to science and

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TABLE 2. Influence of Scientific Studies and Pseudoscientific Reports on Decision-Making (percentage reporting a change in personal behavior)

	Animal Studies	Astrology Reports	N
All adults	74	5	1,635
Age			
17-34	73%	7%	670
35-54	77	4	492
55 and over	74	6	473
Gender			
Female	79	7	862
Male	69	3	773
Education			
Less than high school	71	9	465
High-school degree	75	7	550
Some college	76	3	382
Baccalaureate degree	75	0	146
Graduate degree	78	1	92

technology. In short, a minimal scientific vocabulary is necessary to be scientifically literate.

The 1979 NSF survey included three items—radiation, GNP, and DNA—that may be said to represent basic science and social science terminology. Again, respondents were asked whether they held a clear understanding of each term, a general sense of its meaning, or little understanding of its meaning. Although the accuracy of these self-assessments was not verified, as it was for the understanding of the meaning of scientific study, there is little reason to believe that such checks would not have shown the same discrepancy.[24]

According to the data, about half the respondents thought they had a clear understanding of radiation, about a third thought they understood GNP, and only one in five claimed knowledge of the meaning of DNA (Table 3). Again, there was a strong correlation between knowledge of these terms and the level of formal education.

To provide a single measure of this dimension, a summary index was constructed: a respondent would have to report a clear understanding of at least one of the three constructs and not less than a general sense of a second to be classified as knowledgeable about basic scientific constructs. Exactly half met this requirement. Formal education was once again the key determinant: 96 percent of those

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TABLE 3. Adults Reporting a Clear Understanding of Basic Scientific Concepts

	Radiation	GNP	DNA	High on Index	N
All adults	49	31	22	50	1,635
Age					
17–34	44%	43%	21%	64%	670
35–54	49	30	17	47	492
55 and over	39	23	10	34	473
Gender					
Female	41	21	20	43	862
Male	58	43	26	59	773
Education					
Less than high school	30	7	3	18	465
High-school degree	47	23	15	45	550
Some college	60	47	37	72	382
Baccalaureate degree	70	67	52	88	146
Graduate degree	78	80	57	96	92

holding graduate degrees met the criterion in contrast to only 18 percent of those without a high-school diploma.

Understanding of Science Policy Issues

As science becomes increasingly dependent upon public support, and as public regulation reaches deeper into the conduct of organized science, the frequency and importance of science policy issues on the national agenda will undoubtedly increase. Slightly over half the bills introduced in Congress involve science or technology in some degree,[25] and the establishment of the standing Committee on Science and Technology in the House of Representatives attests to the importance of scientific and technological issues in the national political system.

The 1979 NSF survey provides a useful measure of the third dimension of scientific literacy—the understanding of some of the major public policy issues that involve or directly affect the conduct of science and technology. The survey includes separate batteries of items about three controversies—the use of chemical additives in food, nuclear power, and space exploration. For each, respondents were asked to cite two potential benefits and two potential harms. Approximately two thirds cited at least two benefits or dangers (or one of each) for food additives and nuclear power, but only a third were similarly knowledgeable about the potential benefits and harms

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TABLE 4. Adults with High Score on Selected Science-Related Public Policy Issues

	Nuclear Power	Food Additives	Space Program	High on Index	N
All adults	68	61	32	41	1,635
Age					
17–34	71%	68%	42%	51%	670
35–54	70	63	30	38	492
55 and over	62	52	20	30	473
Gender					
Female	62	60	26	34	862
Male	73	63	38	48	773
Education					
Less than high school	50	37	16	16	465
High-school degree	66	62	28	37	550
Some college	80	75	43	55	382
Baccalaureate degree	87	84	47	68	146
Graduate degree	89	91	58	81	92

of space exploration (Table 4). As with the other two dimensions of scientific literacy, the level of formal education related positively to how well informed the respondent was.

To be counted among those knowledgeable about scientific and technological public policy issues, a respondent had to name a minimum of six potential benefits or harms out of a possible twelve—the single criterion devised to measure this dimension of scientific literacy. Approximately 41 percent qualified.

Using the three dimensions described in the preceding section, a single measure of scientific literacy was constructed that required a minimally acceptable score in all three areas for an individual to be considered scientifically literate. On the basis of this measure, only 7 percent of the respondents—primarily males, individuals over thirty-five, and college graduates—qualified (Table 5). But even among holders of graduate degrees, only a quarter could be called scientifically literate.

IMPLICATIONS FOR A DEMOCRATIC SOCIETY

Assuming that this estimate is correct, that the overwhelming majority of the American adult population is scientifically *il*literate,

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TABLE 5. The Percentage of the Public Classified as Scientifically Literate

	Scientifically Literate	N
All adults	7	1,635
Age		
17–34	11%	670
35–54	7	492
55 and over	3	473
Gender		
Female	6	867
Male	9	773
Education		
Less than high school	0	465
High-school degree	2	550
Some college	14	382
Baccalaureate degree	22	146
Graduate degree	26	92

what are the implications for our political system? How is science policy to be made? Can the basic tenets of a participatory political system be maintained? These issues can only be addressed, I believe, by placing them in the context of the general process of political specialization that has become the hallmark of American politics in recent decades.

Political Specialization

No individual today, no matter how good his or her intentions, can hope to acquire and maintain a mastery of more than a few political issues at one time. Thus the modern citizen who chooses to follow political affairs opts for political specialization—that is, selects out of the myriad issues those few in which he or she is willing to invest the time and other resources necessary to become and remain informed.

The need for specialization springs from a combination of two basic forces. First, participation in the political process is but one of the many demands on the time of contemporary men and women. That many adults choose to devote a smaller share of their time to political affairs, in favor of more attractive, perhaps more personally satisfying alternatives, can be seen in the steady decline of public

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participation in the political system over the last four decades. Even presidential elections, which command the highest levels of public concern and participation, attract barely half the eligible adults in the United States.

Second, the specialized information required to be knowledgeable about almost any given political issue is increasing rapidly. Issues involving science fall into this category, as do most of the issues on the national political agenda. For example, an area like economic policy—often referred to as the pocketbook issue—has become increasingly complex and is beyond the ken of a substantial majority of American adults. If only 31 percent of the adult population professed to have a clear understanding of a term like GNP,[26] how many citizens, then, might be expected to comprehend the current debate over "supply-side economics" or the fate of the dollar in international monetary markets?

Both forces have worked to narrow the political horizon of most American adults. Unlike "single-issue" politics, where the interest of the participant revolves totally around one strongly felt political position, political specialization is a rational and gradual narrowing of the number of topics on which an individual can hope to remain adequately informed. Even then, they are not nearly as well informed about an issue as their interest would imply.

How does this specialization process affect the more general political system? Three decades ago, Gabriel Almond described the process as it applied to public attitudes toward foreign policy and public participation in its formulation. In his original work, he illustrated, in stratified pyramidal form, the types of public participation in the political process that were likely to occur under conditions of issue specialization (Figure 1).[27] At the pinnacle are those who have the power to make binding policy decisions, a group that would include a mix of executive, legislative, and judicial officers. In the case of science policy, the officers would be primarily at the federal level.

Nongovernmental policy leaders, often referred to as elites in political science, comprise the second level. This group interacts regularly with the decision-makers, and from time to time, as noted by James Rosenau and others, there is some flow of elites into decision-making posts, and of decision-makers into the leadership group.[28] When there is a high level of concurrence between the decision-makers and the leadership group, policy is made, and normally there is no wider public participation in the policy process. The policy leadership group may itself divide on some issues. In this case, appeals may be

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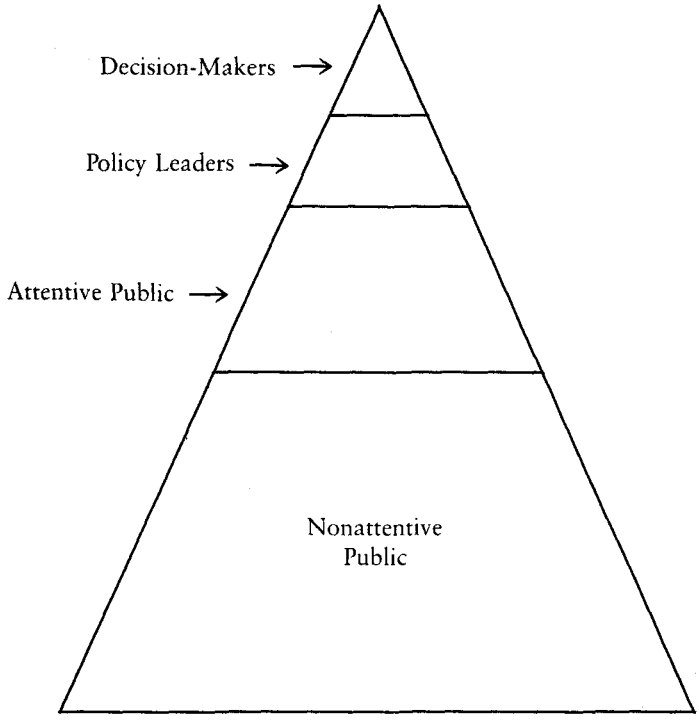

Figure 1. A Stratified Model of Science and Technology Policy Formulation

made to the attentive public—the third level—to join in the policy process and to try to influence decision-makers by contacting them directly and by persuasion. The attentive public is composed of individuals interested in a particular policy area and willing to become and remain knowledgeable about the issue. In 1979 the attentive public for science policy included about 27 million adults, or about 18 percent of the adult population.[29]

Although the processes for mobilizing the attentive public for science policy are only now being studied, the flow of appeals from leaders to the attentive public apparently takes place through professional organizations, specialized journals and magazines, and employment-related institutions. The flow of concerns from the attentive public to the decision-makers, on the other hand, undoubtedly goes through the traditional avenues of letter writing and telephone and personal contacts.

The attentive public also becomes involved when there is a high degree of consensus among the leadership group but a lack of concurrence by some or all of the decision-makers. In this case, the lead-

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ership groups work to mobilize the attentive public to contact the decision-makers and to argue directly for the preferred policy. The recent discussions of federal funding for science illustrate this case.

At the bottom of the pyramid is the general, or nonattentive, public. For the most part, these individuals have little interest in science policy and a low level of knowledge about organized science. Two very important points must be understood about this group, however. First, should the general population become sufficiently unhappy about the policies that the decision-makers, leaders, and the attentive public have fostered in any area, it can exercise a political veto. The public's role in ending the wars in Korea and Vietnam illustrate how powerful this option can be. It is this very ability of the general population to intervene and veto that sustains the democratic nature of the policy formulation process.

Second, it is important not to equate nonattentiveness to science policy with ignorance or lack of intellectual activity. We are all nonattentive to a vast number of issues. Many of the nonattentive public may be well educated, interested in other issues and knowledgeable about them, and politically active. According to the data from the 1979 NSF survey, about half of the adult population in the United States at the time of the survey were attentive to one or more political issues.[30]

Scientific Literacy and the Formulation of Science Policy

Given this stratified decision-making process, the low level of scientific literacy raises two important problems. First, among the 80 percent of the population not attentive to science policy, the level of scientific literacy is extraordinarily low—in the 2 to 3 percent range. In the context of the political specialization process, we would not expect a very high rate of scientific literacy in the nonattentive public, and few voters would be expected to make their choices primarily on the basis of scientific or technological issues. Yet in recent years, an increasing number of referenda have concerned issues related to science or technology—nuclear power, laetrile, recombinant DNA facilities, fluoridation—and it is apparent that a substantial majority of the general electorate will not be able to make informed judgments on these issues.

Second, approximately 70 percent of the attentive public for science policy did *not* meet the minimal criteria for scientific literacy. This is a surprising result, but not an inexplicable one. Almost half of the adult population had a minimal facility with basic scientific terms

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(Table 3), and 40 percent had at least a minimal level of issue information (Table 4). Many of these individuals may have had a high level of interest in one or more science-related issues and may have followed them through popular magazines such as *Science 83, Smithsonian, National Geographic, Discover,* or *Omni,* without understanding the scientific processes involved. They would perhaps have more difficulty comprehending articles in *Science, Scientific American,* or in professional or disciplinary journals, but can undoubtedly write very clear letters to their congressmen and senators. They would appear to be dependent upon science journalists to "interpret" the scientific debate on most issues.

As more appeals are made to the attentive public to pressure directly for public policy outcomes, the importance of this group will grow. Yet, the situation is a fragile one. Given the large numbers in this group who are dependent on "translators," the personality or philosophical perspective of the translator may become as important—if not more so—than the substance of the scientific arguments.

There are compelling cultural, economic, and political arguments for a major effort to expand scientific literacy in both the general and attentive publics. In my opinion, the most effective place to start is in the elementary and secondary schools—a point on which other contributors to this issue will elaborate. Beyond improved science education at this level, I would urge that high priority be placed on the expansion of scientific literacy among the attentive public for science policy, both in terms of increasing their overall numbers and in augmenting their basic level of literacy. What makes political specialization possible is just this basic level of literacy in any given issue area. There is an interested audience searching for more sophisticated information than is normally available in the news media. The extraordinary growth of semisophisticated science magazines like *Discover, Omni,* and *Science 83,* for example, represents in large part the desire for more and better information among the attentive public for science policy.

From Dewey to Morison, the scientific community has been urged to communicate more effectively and openly with the public, especially the informed public—and scientists and engineers are responding by showing a new level of willingness to explain their problems and aspirations to interested lay audiences. But if this communication is to continue and expand so that the science policy process can function effectively, there must be an audience capable of understanding both the substance of the arguments and the basic processes

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of science. We can accomplish this by addressing, without delay, the educational needs of the attentive public for science policy.

ENDNOTES

[1]Martin Green, "A Literary Defense of 'The Two Cultures,' " *The Kenyon Review* (1962): 731-39; Thomas H. Huxley, "Science and Culture," in *Collected Essays* (New York: Appleton, 1898); F.R. Leavis, *Two Cultures? The Significance of C.P. Snow* (New York: Pantheon Books, 1963); C.P. Snow, *The Two Cultures and the Scientific Revolution* (New York: Cambridge University Press, 1959); Lionel Trilling, "Science, Literature and Culture: A Comment on the Leavis-Snow Controversy," *Commentary* 1962, pp. 461-77; Richard Wollheim, "Grounds for Approval," *The Spectator* 1959, pp. 168-69.

[2]Harry Levin, "Semantics of Culture," in *Science and Culture,* edited by Gerald Holton (Boston: Beacon Press, 1965), p. 2.

[3]John Dewey, "The Supreme Intellectual Obligation," *Science Education.* 18 (1934): 1-4.

[4]Ira C. Davis, "The Measurement of Scientific Attitudes," *Science Education* 19 (1935): 117-22.

[5]A.G. Hoff, "A Test for Scientific Attitude," *School Science and Mathematics* 36 (1936): 763-70; Victor H. Noll, "Measuring the Scientific Attitude," *Journal of Abnormal and Social Psychology* 30 (1935): 145-54.

[6]Benjamin Shen, "Scientific Literacy and the Public Understanding of Science," in *Communication of Scientific Information,* edited by S. Day (Basel: Karger, 1975).

[7]Robert S. Morison, "Science and Social Attitudes," *Science* 165 (1969): 150-56.

[8]Davis, "The Measurement of Scientific Attitudes."

[9]Hoff, "A Test for Scientific Attitude," and Noll, "Measuring the Scientific Attitude."

[10]National Assessment of Educational Progress, *Selected Results for the National Assessments of Science: Scientific Principles and Procedures,* Science Report No. 04-S-02 (Denver: Educational Commission of the States, 1975).

[11]Jon D. Miller, "Secondary Analysis and Science Education," *Journal of Research in Science Teaching* 19 (1982): 719-25.

[12]Oscar K. Buros, *The Sixth Mental Measurements Yearbook.* (Highland Park, New Jersey: Gryphon Press, 1965).

[13]National Assessment of Educational Progress, *Three National Assessments of Science: 1969-1977,* Science Report No. 08-S-00 (Denver: Educational Commission of the States, 1978a); and *Science Achievement in the Schools,* No. 08-S-01 (Denver: Educational Commission of the States, 1978b).

[14]Robert C. Davis, *The Public Impact of Science in the Mass Media,* Survey Research Center, Monograph No. 25, University of Michigan, Ann Arbor, 1958; and Stephen B. Withey, "Public Opinion about Science and the Scientists," *Public Opinion Quarterly* 23 (1959): 382-88.

[15]Withey, Ibid.

[16]National Science Board, *Science Indicators 1972*; *Science Indicators 1974*; *Science Indicators 1976*; and *Science Indicators 1980* (Washington, D.C.: Government Printing office, 1973, 1975, 1977, 1981).

[17]Jon D. Miller, *The American People and Science Policy* (New York: Pergamon, 1983); Jon D. Miller, Kenneth Prewitt, and Robert Pearson, *The Attitudes of the U.S. Public toward Science and Technology,* a final report to the National Science Foundation, 1980.

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[18]Jon D. Miller, Robert W. Suchner, and Alan V. Voelker, *Citizenship in an Age of Science* (New York: Pergamon, 1980).

[19]The 1979 survey collected personal interviews from a national stratified cluster sample of 1,635 adults. The field work was performed by the Institute for Survey Research at Temple University, and the interviews averaged fifty-five minutes in length. For a full description of the sample selection methods and the interview instrument, see Miller et al., *The Attitudes of the U.S. Public toward Science and Technology.*

[20]Withey, "Public Opinion about Science."

[21]The questions concerning the understanding of scientific study are illustrative of the limitations and utility of survey measurements. Asking an individual if he or she has a clear understanding of the meaning of scientific study is inherently subjective. Undoubtedly some individuals overestimated their level of understanding, while others underestimated it. Yet, the subjective nature of the response is also its strength, since a person who does not think that he or she understands the term would be unlikely to utilize it in communicating with others. The pairing of this subjective query with the more objective and substantive follow-up definition and astrology questions allowed for a correction for overestimates of understanding in the subjective query. The resulting estimate of the proportion of adults with an understanding of the meaning of scientific study should be taken as an upper limit on the occurrence of this understanding under more rigorous measurement methods.

[22]To be classified as understanding the process of scientific study, a respondent had to report that scientific study involved (1) the advancement and potential falsification of generalizations and hypotheses, leading to the creation of theory, (2) the investigation of a subject with an open mind and a willingness to consider all evidence in determining results, or (3) the use of experimental or similar methods of controlled comparison or systematic observation. Responses that characterized scientific study as the accumulation of facts, the use of specific instruments (i.e., looking at things through a microscope), or as simply careful study, were coded as incorrect.

[23]Donald T. Campbell and Donald W. Fiske, "Convergent and Discriminant Validation by the Multitrait-Multimethod Matrix," *Psychology Bulletin* 56 (1959): 81-105.

[24]As I pointed out in note 21, it is important to note the limitations inherent in these measures. If probes had been employed for this second question, some of the respondents who rated their understanding of these terms to be high would have been reclassified downward. These estimates should be taken as upper limits of the true value in the population.

[25]Shen, "Scientific Literacy and the Public Understanding of Science."

[26]Miller et al., *The Attitudes of the U.S. Public toward Science and Technology.*

[27]Gabriel Almond, *The American People and Foreign Policy* (New York: Harcourt Brace, 1950).

[28]James Rosenau, *Citizenship Between Elections* (New York: Free Press, 1974).

[29]Miller, *The American People and Science Policy;* Miller et al., *The Attitudes of the U.S. Public toward Science and Technology.*

[30]Miller et al., *The Attitudes of the U.S. Public toward Science and Technology.*

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Kenneth Prewitt

Scientific Illiteracy and Democratic Theory

In an earlier era, discussions of scientific literacy focused more often than not on whether nonscientists could achieve an aesthetic appreciation of the complexity, beauty, order, and ever-deepening mystery of the natural world as revealed through science. That theme is little heard today. Appreciation and aesthetics have been replaced by issues of economics and politics. The major issue in the current clamor over scientific illiteracy is about the technical skill-level of U.S. workers, or more broadly, about the decline of the United States in the world political economy. We have heard the argument many times.

Although the United States remains powerful, it no longer stands at the top of the various status rankings that measure political, economic, and military clout in the world. It has lost its number one status. The image of a declining world power, being here edged aside by Japan, there by the Soviet Union, elsewhere by Germany or France, has turned national attention to how we might arrest the decline. There is no shortage of answers to why we are slipping. Religious leaders emphasize deteriorating moral standards; business leaders point to excessive government interference in the free market system; labor leaders suggest mismanagement of the economy by corporate leaders; parents complain about the public education system; the political party out of power blames the party in power, and the party in power tries to deflect attention to all of the above. There are even a few persons—by some called realists, by others defeatists—who say that the dominant role enjoyed by this country in the postwar period was a historical accident and not the result of some identifiable attribute of the American people or their institutions.

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Science leaders, of course, have now supplied their version of why the United States is slipping: the country, they contend, is underinvesting in research and development. It has failed to maintain scientific instrumentation. It is producing a scientifically incompetent population. It cannot expect to compete in the world economy with second-rate engineers, with outmoded equipment, with an untrained labor force. It cannot compete militarily if military personnel are unable to read technical manuals or operate sophisticated weapons. And if the United States cannot compete economically or militarily, its international political leadership will weaken. The causal connection between R&D investment and level of scientific competency, on the one hand, and the standing of the United States in various global stratification rankings, on the other, has become an article of faith among science leaders. A renewed effort in science education is justified in terms of economic productivity, national security, and international political influence.

This perspective touches also upon the conditions under which science is practiced in the United States, suggesting the additional dimension of scientific literacy. Does the public sufficiently understand science that it will support the kind of science policies agreeable to the practitioners of science? Science in this country has long enjoyed a privileged status, and consequently has historically benefited from constructive science policies, which have ranged from benign neglect to active support. But beginning in the 1970s, a new and alarmist note crept into discussions about the place of science in this society. Scientists were no longer so certain of their privileged status. Public confidence in science appeared to be declining. Scientific expertise enjoyed less automatic deference. Public discussion of the actual or potential harm associated with scientific discoveries and their attendant technologies seemed to outpace references to the benefits of science. There was even talk of limitations on scientific inquiry and more than talk about regulations and accounting procedures. Was the public turning antiscience? asked science leaders. If so—and the evidence was confusing—what could be done about it?

Deepen and extend the public understanding of science was one answer. Public understanding of science, so the argument goes, is necessary if the United States is to have reasonable science policies. Public *mis*understanding of science will work its way through the political process and emerge in such detrimental policies as wide fluctuations in science funding, political rather than scientific criteria for

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setting research priorities, unrealistic demands for quick practical results, and misguided regulations or accounting procedures.

There is an obvious connection between the two dimensions of the scientific literacy problem. Misguided science policy can damage the practice of science, and if science itself is impeded, the argument goes, the society suffers. Scientific illiteracy consequently poses a dual problem. It can imply that the population, especially the work force, is unable to maintain the scientific-technical momentum necessary for national growth. And it can imply that the public will fail to provide the support necessary for scientific growth.

These considerations are joined by a third, one that lays open an even more complicated issue in the scientific illiteracy discussion. The metaphor here is not economic productivity or public understanding, but a crisis of democracy. What is to be the foundation of intelligent citizen participation in a society increasingly directed by scientific and technical processes often beyond the comprehension of any save the experts? Can the nation's commitment to equal and informed participation in public affairs be sustained if citizens are scientifically illiterate? Many have written that the prospects for democracy are bleak. Commenting on the "baffling subtleties of contemporary science [which] drift further away from the understanding of lay citizens," Theodore Roszak argues that "one cannot go on indefinitely acknowledging that that which makes one's world go round and mediates all reliable knowledge of reality is hopelessly beyond one's comprehension, and therefore one's control."[1] Or, at least one cannot go on this way and still exercise the rights of citizenship in a democracy.

The contemporary scientific literacy discussion raises in a fresh light an ancient issue for democratic theory and practice. Because the average citizen lives a life far removed from the political, economic, cultural, and technical centers that give direction to society, it has always been a theoretical and practical challenge to ensure that the participatory rights bestowed by democracy will be meaningfully exercised. When the directing centers of society are not within the comprehension of the average citizen, public affairs cease to be public and thus slip out from under lay control.

The late twentieth century brings to this old issue a new set of challenges. The lay public increasingly confronts a political agenda that has been fashioned by technical processes that only the experts can understand. Consider the range of questions on which the citizen is expected to have an informed view. Will fluoridating the water

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system reduce tooth decay? Can statistical modeling estimate the probability of fuel core meltdown in nuclear plants? Are the epidemiological studies sound in concluding that there is no causal connection between Bendectin and birth defects? Can genetic screening of employees reduce the risk of workplace exposure to biochemical dangers? Can radioactive waste material be safely transported and stored? Is insanity a legitimate defense in criminal homicide cases? Has the Green Revolution headed off famine, or has it accelerated the deterioration of the crumb structure of the topsoil? These issues and hundreds of similar ones present models, evidence, and scientific theories that are beyond the comprehension of any save a small number of experts.

I have now briefly alluded to three themes that appear in the current discussion of scientific illiteracy in the American public. The initial theme is the narrowest of the three. It starts from a concern about economic productivity and national prestige, and laments a troubling and worsening situation: the decline in mathematical abilities among students, the lack of preparation in science and math, the declining enrollments in science courses, the empty teaching positions in high-school science and college engineering curricula. These trend lines document the deterioration in science education and in scientific competence even as other trend lines document the rising demands for technically trained workers. The intervention strategy is, of course, focused on the school-age population. Various improvements and reforms are being discussed and in some instances implemented: renewed emphasis on teacher preparation, additional course requirements in science and math, scholarships and prizes to reward scientific and engineering accomplishments, improved classroom equipment and pedagogic aids. But because able and dedicated persons—including several of the authors in this volume—are analyzing this dimension of scientific literacy, it will not receive attention here.

The second theme might more appropriately be called the public understanding of science rather than scientific literacy, although the distinction is fuzzy at times. Public understanding encompasses such issues as confidence in science, willingness to fund basic research, and an appreciation of the conditions under which effective science is practiced. In short, what is at stake is science policy—the ways in which a modern industrial democracy organizes and funds scientific research and training. This theme receives some attention in this essay, although largely as a by-product of my more central concern

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with the third dimension of the scientific literacy discussion, to which I now turn.

II

Clifton R. Wharton, in anticipating the kind of education that will be needed in the twenty-first century, writes:

> more and more people use modern technology while fewer (relatively speaking) understand how it works. Instead, we are content to be served by cadres of technicians and specialists and, thereby, to cede to them an inordinate, even ominous amount of control over our lives. The great mass of people, including many college graduates, are at least arguably in danger of becoming what a recent rather inflammatory book called "techno-peasants": modern-day serfs, nominally free but disenfranchised by ignorance—and fear—of prevailing technologies.[2]

This passage usefully sets the problem, but it does not tell us what kind of scientific literacy will be necessary if citizens are to avoid techno-peasant status. Although we might wish for a society in which citizens can read *Scientific American,* it would be a wish begging to be frustrated. It is not easy even to find a scientist who can read through *Scientific American.* But if we are not talking about the substantive knowledge commonly assumed by the phrase "scientific literacy," what are we talking about when we worry the issue of democratic participation in a technical society?

This essay will make use of the term *savvy.* We speak of savvy people as those persons who act on the basis of a shrewd understanding of the deeper principles and structures that govern complex situations. A savvy person has those skills and insights that make for survival and success in what would otherwise be bewildering and intimidating situations. Political savvy, for instance, is familiarity with the informal rules, the operating codes, the levers of power, and the folklore of an ongoing political process. Entrepreneurial savvy is the know-how necessary to make the intricacies of the marketplace work on behalf of new ideas and new products.

Perhaps the most suggestive use of the metaphor is in the slang phrase "street savvy" or "street-wise." Street savvy separates the outsiders from those in the know; it reduces confusion and seeming chaos on the streets to known rules, predictable patterns, and understandable hierarchies. It is a second sense about why things happen as they do. Situations that to the person lacking in street savvy are

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threatening are to the savvy resident the commonplaces of life on the street.

If we carry the metaphor into our discussion of scientific literacy, we can speak of "savvy citizens" as those not bewildered or intimidated by the introduction of new technologies or the arrival of new scientific languages. The scientific-technological underpinnings of the society are familiar turf. By definition, savvy citizens are not outsiders in their own society. Rather than being manipulated (or feeling manipulated) by forces beyond understanding and beyond control, the citizen "in-the-know" can make the system work.

Scientific savvy is hardly a new idea. It is one way of describing the practical knowledge possessed by members of any functioning society. Malinowski, in the opening paragraphs of his classic essay on magic, science, and religion, writes that

> a moment's reflection is sufficient to show that no art or craft however primitive, could have been invented or maintained, no organized form of hunting, fishing, tilling, or search for food could be carried out without the careful observation of natural process and a firm belief in its regularity, without the power of reasoning and without confidence in the power of reason; that is, without the rudiments of science.[3]

Malinowski describes in some detail the scientific principles and technical skills brought to bear by the Trobriander sailors, fishermen, and farmers. Similar documentation has been provided by many anthropologists reconstructing the economies and polities of so-called prescientific cultures. A shrewd understanding of winds and rains and storms, of insects and seeds and soils, and of animal habits and edible plants, has long been the scientific lore of fishing, planting, and hunting cultures.

We make no claim, then, that in introducing the notion of scientific savvy we are suggesting anything new. The newness is not in the notion, but in the content. What is the American citizen's equivalent of the Trobriander's confident understanding of hydrodynamics and equilibrium, such that he would launch his outrigger in threatening conditions? The division of labor anticipated by Adam Smith and sociologically described by Durkheim has moved us a long distance from the Trobrianders, as of course has the exponential growth of scientific and technical knowledge.

In reaching toward an understanding of what will constitute scientific savvy, or street wisdom, for the citizen of an advanced industrial

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democracy, I want to start with a distinction between the personal and the public. By personal, I mean those things that would help a person effectively apply the principles and products of science in his or her own life. As suggested in this volume by Barton Childs and Faith Hickman, parents, or potential parents, need to understand the benefits that antenatal diagnosis can provide. To generalize the point, the revolution in biology has opened up the whole field of behavioral health, which has brought within the reach of many citizens the prospect not only of longer life, but of a longer, healthier life. To be shut off from these discoveries by scientific illiteracy is to be denied the personal benefits of modern science. Similar examples could be given in such nonhealth fields as computers and electronics, which have laborsaving potentials even greater than the mechanical inventions brought into personal use by the scientific and technical work of the late nineteenth and early twentieth century.

But of course it is not in health-related behavior or laborsaving devices that scientific savvy is of most importance at the personal level. The area that understandably receives the most attention is employment. Persons bewildered by modern technology are denying themselves employment opportunities in an economy resting on an ever more complicated technical base. If the Trobriander farmer needs a workable knowledge of soils and seeds and rainfall, the contemporary farmer in the United States needs a workable knowledge of insect physiology, chemical fertilizers, weather modification techniques, hybrid strands, animal breeding, mechanized and computerized support systems, price supports and parity, and international commodity agreements and trade patterns.

There is no end to examples of how scientific savvy can benefit the parent, the consumer, the employee, the producer, or how the lack of it could limit their opportunities in serious ways. And much of the scientific literacy discussion is pitched at this level. Schools should teach science in a manner that opens up personal opportunities for all their graduates, not just for those whose career choice is science or engineering.

At the personal level, scientific savvy has to do with effectively coping, or with what Mary Budd Rowe in a companion essay has termed fate control. But we are also concerned with the citizen's involvement in public life. In this domain we have a less clear view of what might constitute scientific savvy. It is the question I take up in the remainder of my paper.

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III

If the economic and political life of our society rests in important ways on a scientific-technical base, we can hardly claim that public affairs are in the hands of the public when citizens are poorly informed or misinformed about science and technology. The problem with this oft-repeated truism is that it fails to identify the scope and form of information necessary to ensure democratic politics. Or worse, the truism makes the facile assumption that citizens, if only we can get our educational system straightened out, can acquire a substantive understanding of scientific principles and discoveries. This may be true for some of the citizens somewhat, but if the future of democracy rests upon a substantive conception of scientific literacy, the prospects are not good. To franchise only those citizens who can understand the scientific principles behind a missile program, a toxic waste disposal system, a cancer cure, or a genetic screening program, is to franchise only a small part of the populace.

From the perspective of democratic practice, the notion of scientific literacy does not start with science itself. Rather, it starts at the point of interaction between science and society. My understanding of the scientifically savvy citizen—in contrast to the scientifically savvy parent or consumer or employee or producer—is a person who understands how science and technology impinge upon public life. Although this understanding would be enriched by substantive knowledge of science, it is not coterminous with it. This argument can be worked out under three general headings: the political process; public policy-making; and social change. In each instance, I barely begin the conversation, but in each, I hope to indicate that there are some fundamental principles which, if understood by the lay citizen, could help preserve a democratic polity despite the expanding technical content of many public issues.

The Political Process

A familiar complaint is that the issues on the political agenda often have technical dimensions beyond the comprehension of practically all citizens, issues such as radioactive waste management or arms reduction or genetic engineering. What is a democracy to do when the premises of major issues can be understood by only a fraction of its population? About the best that democracy's defenders have suggested to date is to introduce into the political process the practice of countervailing expertise. In technical controversies, if the lay citizen

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cannot make an independent judgment, the citizen must at least be exposed to the arguments of contending experts. This is the "science court" writ large, a procedure to be used not only for scientific disputes, but also for an increasing number of public questions with technical content. There are two problems.

First, and most fundamental, the practice does not preserve democracy, at least not as we commonly understand it. To reinforce the citizens' reliance on experts is to confirm them in their fear that their practical judgment no longer has much to suggest to the big issues of the day. Roszak, I believe, asks the right rhetorical question of countervailing expertise.

> Does our democracy not continue to be a spectator sport in which the general public chooses up sides among contending groups of experts, looking on stupidly as the specialists exchange the facts and figures, debate the esoteric details, challenge one another's statistics, and question one another's prognostications? It is difficult to see that, in the long run, such a counterbalancing of expertise can be a real victory for the democratic autonomy of ordinary citizens. They remain expert-dependent.[4]

Second, to rely on countervailing expertise is to invite fraud. I have in mind the fakery that travels under the guise of pseudoscience: creation science, astrology, parapsychology. It may be a backhanded tribute to science that even wholly unscientific doctrines cloak themselves in scientific terms. But this indiscriminate use of scientific terms carries a warning to those who would depend on countervailing expertise as a method of preserving lay control in issues such as nuclear siting or fluoridation or school curriculum. Not all citizens know enough science to sort out the reasonable from the unreasonable, geology from flood geology. A political process that invites demagogy, as excessive reliance on expert testimony might, obviously would move us away, rather than toward, democratic practice.

To protect democracy will require framing public issues, even those with scientific and technical content, such that they are accessible to the lay citizen. This will primarily involve bringing to public attention the consequences of science, insofar as those can be known. We might start by examining the phrase "knowledge for its own sake" from a political as well as scientific perspective. The scientific perspective is well known: knowledge lays a foundation for more knowledge. But from a political perspective, to assert that the knowledge process simply feeds the knowledge process is misleading. Scientific knowledge serves purposes that reach far beyond the research

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life of science itself. These purposes are economic, political, and military. The citizen who takes at face value the "knowledge for its own sake" metaphor is doubly disenfranchised. Such a citizen has only a partial understanding of science and an even more limited understanding of politics and economics. Unless it becomes clear to citizens that the purposes of science—not at the margin, but at the core of the enterprise—are commercial, strategic, and bureaucratic, there can be no democratically involved populace. In teaching this lesson, we need not be cynical about science and about the necessity for free inquiry undirected by immediate purposes. This correct, but partial, image of science can be protected. But it should be joined with another image of science, one much more politically realistic. It is not without political significance that federal R&D spending, for instance, is allocated about one half to defense, one seventh (14 percent) to space, and only about one third to civilian purposes. Nor is it without political significance that about 80 percent of the expenditures are in applied research and development, the remaining 20 percent being in basic research.[5] The federal budgetary allocations reflect judgments about the purposes of science, as do the allocations that characterize the commercial sector.

Scientific literacy, at least from the perspective of democratic practice, encompasses an understanding of the nonscientific purposes of science. For it is on these matters that the citizens are most frequently asked to vote. Scientists do not aid in this cause by claiming that knowledge is something sought just for its own sake.

Policy-Making

A good deal of public policy-making starts from some guess about what the future will look like if some intervention is either attempted or, having been considered, is rejected. To think intelligently about public policy, then, is to think about present trends, extrapolations of those trends, and likely outcomes associated with different interventions. A scientifically literate populace would understand two things about policy-making; first, that the various scenarios of the future with which the policy process must contend are themselves often consequences of developments in science and technology; and second, that our views toward what is and may happen derive from science-based forecasts.

Forecasting is not, of course, the same thing as prediction. Scientific prediction relates the behavior of phenomena to known antecedents or independent variables. A prediction is a scientific statement

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about cause and effect. Forecasting, which scientists also practice, has to do with the future. More specifically, it has to do with the possible shape of the future if present trends are extrapolated.

Forecasting may or may not have a scientific base. Many forecasts start from religion—Repent, or suffer the wages of sin. Others start from politics—Arm the nation, or risk foreign invasion. Others start from economics—Reduce the deficit, or expect an economic depression. These forecasts are all guesses about the future based on extrapolating present trends and on analogous comparison to historical experience.

It is the mark of a scientific culture that so many of our forecasts today start from scientific findings. Sometimes it is the individual's future that is being forecast—Smoke heavily, and die of lung cancer. Sometimes it is the environment's future—Large-scale consumption of fossil fuels, releasing carbon dioxide into the atmosphere, will raise the average temperature of the earth's surface. There are demographic forecasts about human populations—If forecasted fertility rates and life expectancy changes occur, the earth's population will grow to between 9.8 and 10.5 billion, before leveling off a century hence. There are attempts to forecast technological events, as in the statement of probability of an accident in a nuclear power plant. There are scientifically based statements about the probability of natural disasters, earthquakes and floods, that are ignored at great risk by those in the likely paths of such disasters.

These forecasts have many things in common, not least of which are the high stakes of believing/disbelieving them. The greenhouse effect, for instance, will alter agricultural production around the world, moving the gradient of warm temperature northward and the gradient of rainfall westward. The greenhouse effect will alter the global ecology as the Arctic permafrost retreats and tropical rainfall increases. Human health will be affected as disease agents and agricultural pests migrate and reproduce in unforeseen ways.

Furthermore, the trends on which all these forecasts are based can be interrupted by changing present behavior. This is most easily seen with respect to preventive medicine—Change smoking habits, diet, life-style, and so on now, and benefit forty or fifty years hence. Of course the same preventive action can happen at a collective level, as illustrated in the birth control practices introduced in India or China, the energy sufficiency policies of the United States, or the laws that regulate residence in flood plains or earthquake-prone regions.

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The type of forecasts I speak of have three important properties: they are based on a scientific understanding of the natural or social world, or often of the interaction between the two; they address issues of great, if potential, harm or benefit; and the trends that the forecasts are based on can be self-consciously interrupted by changes in individual behavior and social policies.

An important dimension of public policy is dealing with the increasingly numerous forecasts that have these three properties. It is not easy for the lay citizen. The forecasts based on science are often stated in probability terms, so the citizen needs some understanding of statistics. A citizen able to evaluate critically probability statements based on scientific evidence will have enough common sense to know it is not true that "everything will cause cancer if you give enough of it to a rat," and consequently will be able to assess whether to eliminate from his or her personal diet those toxic substances that science has linked to cancer. This does not imply that every citizen need become a statistician. It does suggest that citizens acquire a nontechnical understanding of such basic statistical principles as the law of large numbers and sampling error. Similar to these statistical principles is the companion principle of "all things being equal." Forecasts based on scientific evidence are advanced with the qualification that confounding factors are being held constant, even when it is known that factors exogenous to the model will change and thus affect the accuracy of the forecast. But there could be no statement about the future without invoking the principle of all things being equal. The nonscientist needs to understand this, else the ability to evaluate forecasts will be seriously impaired.

Finally, we take note that forecasts very often are controversial, scientifically as well as politically and economically. They are scientifically controversial because the evidence is less than conclusive. Scientists and scientific evidence will be found on more than one side of the question.

Because science-based forecasts are frequently controversial, we cannot separate scientific savvy from the ability of citizens to engage in moral reasoning. A science-based forecast often must be evaluated against moral standards. Moral reasoning is both prescience and postscience. It helps us ask what it is we want to know; it also asks questions about the human implications of what we have learned. Life-extending technologies in medicine, for example, while resolving certain biomedical questions, raise in the process numerous ethical issues. Science—always—is surrounded by moral questions. This is

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especially true of science-based forecasts that suggest the need to alter present behavior in order to realize future benefits for oneself or for society generally. Against what moral standards do we restructure social arrangements in the present to avoid some less-than-certain future risk or to achieve some less-than-certain future benefit? Citizens unable to reason morally will be poorly equipped to think about different scenarios for the future. In this sense, there can be no scientifically savvy population that is not also morally savvy, and no democratic discourse that is not also moral discourse.

These comments about forecasting lead directly to our concern with the connection between scientific literacy and democratic practice. Tools, it is said, extend our physical powers, telescopes extend our visual powers, decision-logic extends our reasoning powers, and so forth. Science-based forecasts do no less than extend our powers to make judgments about the kind of world we want to live in—or avoid. Citizens who cannot evaluate the merits and probabilities of science-based forecasts have as surely forfeited a measure of control over their future as if they took no note of the coming and going of political regimes and ideologies.

Social Change

Science—or perhaps here we should speak more directly of technology—for all its consequences in social life, does not introduce change in ways that are linear, predictable, or even much understood. This suggests that a dimension of scientific savvy is familiarity with a few basic principles about how science and technology operate on society.

A useful place to start is with the "bittersweet" principle of technological change. To innovate technologically is not just to offer new social benefits, it is also to impose social costs. Major changes made in the social order will always undermine some social values, harm some social interests, and penalize some social groups. There is no Pareto optimal technological change. At a minimum, persons whose livelihoods were dependent on the now-outmoded technology are likely to suffer. More likely, the transition from the old to the new technology—from carriages to cars, from assembly lines to robotics, from family farms to mechanized agribusiness—will involve many social groups and will sweep across various facets of social life, and not in a manner of immediate benefit to all those affected. The bittersweet principle can clarify public discourse about new technologies. Its acceptance would help the public understand that there will be

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costs to pay as well as benefits to enjoy, and the public will enter the political debate better equipped to discuss the allocation of the costs as well as the benefits.

Related to the bittersweet principle is the law of interaction effects. In interdependent systems, it is not possible to deal with one large component without disturbing other components. This systems principle is a commonplace to persons who think much about technology and society. It is apparently not a principle generally accepted in American political discourse. Consider the three goals of environmental protection, energy sufficiency, and economic growth, goals certainly comprising a tightly interdependent system. Yet we have a politics in which different, and antagonistic, interests gravitate to one or the other of the goals—environmentalists to environmental protection, pronuclear advocates to energy policy, and large-scale capital to economic growth goals. Politics won't disappear with a population appreciative of interactive system affects, but the terms of political discourse would become more reasonable.

A third principle of technology in society is suggested by sociologist Robert K. Merton, who has called our attention to the unintended consequences of purposive social action. There are unintended, and inevitable, second-order consequences to the introduction of new technologies in society. Again a commonplace. Obviously, the automobile changed how we used space; television has changed the educational process; electronic communication has made possible the growth of multinational corporations, thereby altering the international economic order; robotics will change work habits and the work force. But a savvy public needs to understand the inevitability *and* unpredictability of second-order consequences, which in turn have their own consequences. And so it goes, in an endless spiral.

The bittersweet principle, the interdependent properties of technosocial systems, and the rule of unanticipated consequences combine to caution us not to expect—or even want—a technological fix. Complex problems don't have simple answers. A savvy population recognizes a "fix" for the unrealistic goal that it is. It is the rare problem that is solved; more often, the problem changes form. To control infectious diseases is not to solve the health problem. It is to shift attention to cancer and heart failure. And when these illnesses of late middle life are cured, the health problem will shift to senility and related illnesses of the aged. Society copes with problems; it doesn't solve them. If the public is to become actively involved in debates over the introduction of major technologies—chemical fertilizers,

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fluoridated water, nuclear energy, genetic engineering—then the minimum literacy necessary is appreciation of this fact.

IV

The public discussion of scientific literacy will be with us for some time, as will be the three dimensions touched upon in this essay. Insofar as the emphasis is on the technical competence of the work force, it will take many years to improve precollegiate and collegiate education, as well as to institute appropriate adult training programs. Other essays in this volume testify to the seriousness of the problem and the difficulty of designing and implementing solutions.

The problems are no less great when attention turns to the public understanding of science or, more appropriately, of the public's understanding of the conditions that ensure the effective practice of science. Part of the difficulty here derives from our inadequate theories about public opinion as it impinges on science policy and science funding. I have argued elsewhere that the public probably knows more about science than scientists know about the public—"the scientific community has often shown itself to be ignorant about the way in which public attitudes are formed and become expressed through the political participation system."[6] Although some renegotiation of the contract between science and society, to use a favored metaphor, is under way, this renegotiation need not damage science. Such basic principles as peer review, minimal restrictions on inquiry, international exchange of scientific findings and data, long-term funding, and the setting of research priorities by scientists can be protected. The place of science in the public's esteem is reasonably secure, and such damage as science is likely to suffer will more likely come from scientists' misunderstanding of the public than vice versa.

The most complicated questions are raised by the third aspect of scientific literacy—what constitutes informed public involvement in the political life of a nation increasingly directed by advances emerging from science and technology. Now we are into the thicket of democratic theory and democratic practice, but around a set of problems not anticipated by our forebears. There are no ready solutions. But unless we begin to sort out the issues involved, our efforts to train a more competent work force or to design workable science policies will only scratch the surface of what should constitute scientific literacy in a democracy. To repeat the argument advanced in these few pages, we need a conception of scientific savvy that will connect to-

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day's citizen with the public life of his community in as meaningful a way as did the scientific lore of the hunting, fishing, gathering, harvesting, and farming cultures that preceded modern society. Working out this conception will be difficult enough, but it is only the initial step. A reformulated "theory of democracy" will then have to be put into practice, which will involve the public education system in a task not unlike that of an earlier century, when a mass population was introduced to the norms and rules of democratic politics.

ENDNOTES

[1]Theodore Roszak, *Where the Wasteland Ends: Politics and Transcendence in Post-industrial Society* (New York: Doubleday Anchor Books, 1973), p. 239.
[2]Clifton R. Wharton, Jr., "Curriculum 2001: Education for the 21st century," Chancellor's Report to Faculty Senate of State University of New York, April 10, 1981, p. 3.
[3]Bronislaw Malinowski, *Magic, Science and Religion* (New York: Doubleday Anchor Books, 1955), pp. 17-18.
[4]Roszak, *Where the Wasteland Ends,* p. 50.
[5]See *Science Indicators 1980,* report of the National Science Board, 1981.
[6]Kenneth Prewitt, "The Public and Science Policy," *Science, Technology, & Human Values,* no. 39 (Spring 1982):5-6.

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David Hawkins

Nature Closely Observed

THERE IS A MARVELOUS CONTINUITY between the worlds of children's experience and the adult worlds of the arts, of the sciences and mathematics, of conduct and social life. This continuity is one of cumulative learning. Learning, in this educationally important sense of the word, is always in principle spontaneous. Man, said old Korzybski, is a time-binding animal. We store experience, well or badly, as the squirrel stores nuts. Not for a coming winter, though in a winter time the store may save us. But learning is also always, in some degree, *induced.* In this essay I wish to use both these words, in a sense as technical terms. For *spontaneous,* I go back to the Latin *sponte,* of one's own accord, and still later to an Indo-European root *spon,* which is one of that vast collection of words derived from the weavers' art, to spin.[1] In the hand of the spinner, the spindle is given an initial twist, but it continues for a time spontaneously, of its own accord or, as we may prefer to say, its own spin energy. Children only learn well of their own accord. In this case, we need not wind them up to start the process; nature does that. But in another sense, the learning they engage in can be induced; they can be led into association with matter that matches their readiness to assimilate and to make much of that which counts and that they might otherwise never gain access to. Induced learning is still, for children, spontaneous, if they are led, not dragged. When children are only dragged, they learn to cope with a curriculum of intimidation. To teach, then, is to have the authority of the guide, of one who shows the way. To teach is not to drag, though some element of the imperative mood is always latent in teaching; the guide who shows the way is never merely permissive. When children have been brought into some fresh territory for exploration, and find in it some

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joy and satisfaction, they forgive the hand that sometimes had to push their noses into such milk. But mostly, the hand is not needed; trust can take its place. And an attentive guide is open to questioning, to the suggestion of alternative routes.[2]

So what anthropologists call the transmission of culture is not at all the sort of telegraphic imprinting that the word itself suggests, but rather an enormously complex and problematic concept. At its best, the continuity between generations means that babies can grow up to be inventive women and men; children who have been excited by learning can later become adults who infect new children with that same excitement, supporting their entry into the great world, maintaining and advancing the qualities of life, of all that which over hundreds of millennia has increasingly set us apart from our sheer animal existence.

But there is also a dreadful continuity between the limitations and failures of one generation and those it visits upon the next. Under deprivation or duress continued too long, children are not able to find those affirmative choices that would enhance their lives. As they enter the streams of adult life, they often must take with them their miseries, their accommodations to failure, even to brutality. They then may themselves sow dragon's teeth, a crop their own children will in turn harvest and replant, sometimes in even greater measure.

Such connections, educative and miseducative, are powerful; they are the counterpart for cultural evolution—including the rise and fall of cultures and civilizations—of all the genetic transmissions and changes that evolutionary biologists are concerned about in the history of terrestrial life. As a product of that biological evolution, we are predisposed to care for the young for some major fraction of their whole lives, to bring them up and to educate them over the long years of infancy and childhood. Disposed in their turn to assimilate what the adult world can offer them, children may assimilate and respin its strands and reweave its wefts of competence and creativity. They may also, in self-defense, emulate its self-destructive capacities. If our best and most insightful nursery schoolteachers could be transformed by some magic into anthropologists and historians, I think they would look for a different sort of evidence than historians have mainly offered to explain the rise and fall of cultures and civilizations: they would look to the transmission of cultures and of the zeal to learn, or to the failures of education thus broadly defined. The task would not be an easy one; the detailed processes of culture

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transmission have long been practiced but seldom much noticed or recorded; the exercise of sheer habit can go for long unquestioned.

I have spoken about the extremes of the process, the best and the worst. More frequent than either, of course, is a pattern of partial education to which we have become too well accustomed.

In the total ambience of children's lives, then, there exists always some educative potential of which the school is only one component. The other components of this potential for education or miseducation—family life, peer association, and the big world they increasingly respond to—are in many ways more powerful than schooling. Schools are, after all, only an institutional invention, and in the long sweep of history, a recent and still very uneven one. But even today, children of the well educated often likewise emerge as well educated, along pathways that owe less to their formal education than might appear. Teachers are prone to claim more in this regard than is really justified. On the other hand, where the out-of-school potential is low, school can be a vital alternative. This is often true for those from generally meager backgrounds; and where the educative potential of some major part of society is in fact low, then what can be learned in school can become a saving grace, ameliorating the dreadful continuity. In saying this, I do not wish to minimize those informal extensions of formal education, intended for adults and children alike, represented in our day by film and television and by museums. As extensions of schooling, they can enrich the ambience, at least for some.

I have begun with these rather wide-ranging remarks because I wish to discuss an educational domain in which the spontaneous potential of even our otherwise well-educated classes is on balance quite low: mathematics and the sciences. We are all acquainted with the extraordinary history of rapid social change that, over three or four centuries, has been coupled with the evolution of the special subculture of science. This subculture of science has owed its vigor, as a necessary condition, to its ability to reproduce itself on a scale that has steadily increased. This increase is in numbers, in detailed knowledge reduced to order, and in specialization. Thus an important part of the history of science has been the recruitment of the young. To this end, science has long since invaded the universities, and now in some manner can dominate them. Its influence is far less in the secondary schools, and almost negligible in the first six or eight years of schooling. Along the way, however, and perhaps as a neces-

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sity of rapid growth, the scientific subculture has developed such cumulatively special ways of learning, of reorganizing, and of communicating as to constitute increasing barriers to entry. The required preparation of neophytes has become more and more extensive and elaborate, and there is finally a threat of their sheer depletion. The well is not dry, but the needed talent level has been steadily lowered. Some of us have come first to a new concern for earlier and wider science education because of this threatened depletion, a threat to the continued prosperity of our craft. The wells of available talent must now somehow be refilled and maintained by earlier and wider and more effective science education. Such is the narrow view. The institutional statecraft of science has for a long time taken too much for granted, beginning its educational efforts too little, too late, and with too little attention to quality.

There is a wider view, however, concerned less immediately with recruitment than with the welfare of a society that on the average has so low a diffuse out-of-school potential for science education, but that depends crucially upon the institutions of science and upon their increasing symbiosis with industry, with medicine and agriculture, with government and with the military. Our aim in teaching basic science should be to prepare all youngsters for eventual participation in the democratic discussion and reordering of ends; the narrowing, even the failure to broaden basic science education, creates scientific and technological oligarchies, while the rest of us tend to become incompetent for democratic rule, to become—in the language of Toynbee—a cultural proletariat.

Both these honorable views, which have become very familiar to us, are clearly not incompatible. If the range of scientific literacy is widened, the diffuse educative potential increases, and the level in the wells of talent will also rise. Twenty years ago we argued—or at least competed for educational funds—in terms of the ordering of priorities as between upper-level professional science education and lower-level science for the citizen. Now, I think, this sort of debate seems rather stale and innocuous. We need both equally, each for the other.

But there is a third, a still wider view, growing out of good works that have often been attempted but not widely credited or understood. There are beginnings of it in the traditions of enlightenment; surely not, however, much reduced to widespread practice, and perhaps least so among the official austerities of present-day formal education. I think it is a view necessary to the empowerment of the narrower views I have summarized, but it has more important justifi-

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cations as well. I shall elucidate it, as best I can, from the educational lives of children and of those who teach them. It is most accessible there.

In this wider view of science education, the central aim is to contribute, quite generally, to the improvement of *all* education. As such education should prove successful, it would of course contribute to enlarging the pools of potential scientific talent and enhance the qualities of intelligent citizenship. But such aims are thin gruel; they lack the kind of informational richness we need to guide our efforts. They may indeed only lead us today—in a new round of concern—to intensify conventional efforts already marked for failure. I propose to start instead with some account of what I believe to be our most successful experience. I cannot document it on any but a small scale, out of the experience of good teachers I have had the luck to know. It also fits a certain good theoretical mold, however, which supports it and which I shall try to sketch.

In singling out our present-day inadequacies for teaching science and math, and then in proposing a direction for remedy, I may seem to risk a false assumption: that all else is well in our early education practice. It is a risk made all the more obvious by the widespread talk of the deterioration of schooling, usually in the areas of reading, writing, and computational skill. But there is the opposite risk, that we fail to recognize the ways in which children's early involvements with the substance of science and math can open gates for them, into all the domains of knowledge and enjoyment. I shall try to compensate for the first risk by doing what I can to avoid the second.

As a first step, a basic assumption: to lead children into domains of science and math can presuppose less, by way of any prior richness in their educative backgrounds, than is needed for other essential parts of a school's curriculum. History, for example, or literature, even reading and writing, can come easily to children whose family and social background provides them, early and steadily, with surroundings where such matters are valued as part of daily life. For those who lack that sort of background, these interests can be relatively inaccessible. There are exceptions, of course; but when we look closely there, among the children of poverty, we seem to find only rare, special circumstances that have opened the doors for them into the worlds of the written word, of the arts and humanities. The sheer fact of poverty does not always exclude those drops of nectar in the sieve that can heighten children's taste for poetry, for fantasy, for storytelling, and so for the written word. Nevertheless, such engross-

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ing interests presuppose an early richness of experience and of experience reflected upon, which the life of poverty can seldom afford.

If we follow this line of thought, we are led to the conclusion that there is more of the basic background experience for mathematics and science in the life of every child than for most other subjects in the early curriculum. These are the daily phenomena of nature that surround us constantly, early and late, and about which we all accumulate a central store of experience—of light and dark and color, of heat and cold, of motion and rest, of forms of matter and of life. In a trial course of geometry, the *Gruppo Scuola e Università* in Rome, for example, introduced planes, lines, and points by slicing a potato at right angles once, twice, thrice.

But this conclusion seems in violent contradiction with the everyday wisdom of curriculum designers and of most teachers. Math and science are reputedly the most difficult subjects to teach. As a result, science is taught hardly at all, while math is reserved for the early hours of the day when children are, it is supposed, least fatigued. If this belief is correct—and it is surely based on massive experience of a kind—then something is very wrong with my line of argument, which implies that of all the traditional subjects in the curriculum, math and science should in principle be the most accessible to children from a wide range of backgrounds. But I prefer to take refuge from evidence of this sort. There is an old joke: "Don't confuse me with the facts!" I think the facts are there, but they are wrongly taken. Early math and science are on balance so badly understood and taught that the failures we know so well lie with the style of teaching and hardly at all with the children. School failures are typically regarded as children's failures, rather than failures of the school itself. There is very little evidence readily available to decide between my own belief and that which usually prevails; we have many would-be child doctors, but too few school doctors. Against a mainstream of opinion that I reject, I reaffirm my argument: the kind of experiential background in children's lives before schooling begins, or along the way, is more uniformly adequate to math and science than to most other school subjects. The poverty or riches of social background matter less here in the early years than in other school subjects. Math and science should therefore be the great equalizers, whether they are now seen to be or not.

I have said that in our elementary schools, science is seldom taught at all, while math is reserved for the early hours of the day. But that is inaccurate. I should have said that neither subject is taught, for the

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most part, at all. What is called school mathematics is not mathematics, or is barely so. The lives of children in elementary school are dominated during "math" periods by assignments that are only called arithmetic. A tiny bit is called geometry, but most of that bit dwells on the mere names of things unloved, such as triangles, squares, pentagons, and the like. Most of what is taught is called arithmetic, and children learn, soberly, to add, subtract, multiply, divide. They also may learn some bewildering rote algorithms about fractions, how to add or subtract, even multiply or divide them. They learn, in a fashion, to handle negatives or decimals. And this modest goal takes six or eight years of dubious battle; a thousand or two hours, central hours, of children's days for 10 or 20 percent of their lives.

The ancient Greeks made a distinction in their language between what they called *arithmetic* and what they called *logistic*. Arithmetic was the investigation of the world of numbers; logistic was a set of rules, to be memorized, for doing rote sums, differences, products, quotients. Arithmetic was a kind of science, always fresh and open to endless investigation. Logistic was a dull art, needed for bookkeeping and other such practices, which you could learn by rote. If you understood something of arithmetic, you could easily master the rules of logistic; if you forgot those rules, you could reinvent them. What we mainly try to teach in all those early years of schooling is logistic, not arithmetic. We drag, not lead, and the efficiency of learning is scandalously low. Of course, it is not all one way. In order to pursue arithmetical investigations and the many practical uses to which some can be put, it is useful to deal easily with sums or quotients. In some purely formal order of development, the rules come first.

But, in the order of optimal understanding, the intuitive grasp can often run far ahead of the computations necessary for completely reliable answers to questions that a budding curiosity has raised. We put poker chips together on the table in the patterns of triangles or squares, and find that these patterns can grow larger and larger, yet preserve their shape. It can be an invitation for counting, for tabulating, for seeing relations of sum and product and quotient. We begin to see a pattern of number growth in the patterns of shape; we predict and perhaps confirm; we find nice relationships between the visual world of geometric form and the step-by-step logical world of number. These are small examples of the vast array of relationships that cross-connect two very important domains within all our experience—number and form—which early schooling, if it treats them at

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all, too often treats in isolation. It is a simple and shocking example of this separation that, to most elementary schoolteachers in the courses I teach, the adjective *square,* when applied to numbers, has no perceived relation to the same adjective applied to shapes. Even triangular numbers, not to mention pentagons, cubes, or tetragons, are then a complete surprise, as are other classes of number shapes.

Many investigations into the connections between number and form are quite accessible to children and bring new understanding. Along with the many practical uses of math that can engage children (carpentry, sewing, weaving, classroom bookkeeping, mapping, and measuring), the genuinely mathematical investigations can motivate the acquisition of computational skill, of logistic. This skill is—or should be—subordinate to real math, and when subordinated, can be learned more easily. In all of this, one can live and work in the style—often the very content—of the ancient Greeks before Euclid. In the three centuries before his works appeared, there were many little and some big mathematical discoveries made. Those early mathematicians, and many still later, used the letters of the alphabet for numerals and the abacus for computations, and drew shapes in smooth sand. The language they used was just the ordinary Greek; there was no elaborate shorthand symbolic notation such as we associate with present-day mathematics and force too early upon our children. But from such everyday beginnings, the ancients began to develop some powerful ideas and important questions, the beginnings of our own tradition. Children guided can do that, too.

A classroom in which this sort of real mathematics is pursued becomes a math lab—I call it the Laboratory of Archimedes—and by an easy extension, it can also become a science lab, with much of the simple apparatus for investigating physical phenomena (heat and light, sound and motion), and with space for various growing plants and sometimes resident or transient animals. And since all important matters that transpire in such a classroom must be related to what one finds in books, there must be a good library corner. Good things must also be reported on, with texts and posters. (A "nonreader" will learn to use them if they contribute to learning, and will learn to write if there is fresh excitement to communicate.) In its contrast with most classrooms we have seen, it may sound forbidding, but it is in fact the opposite. It is most inviting.

I recall, with amusement still, a class in North Wales, in which a group of ten-year-olds put old Galileo to the test. A children's science book had told the too-simple story of the unequal weights dropped

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from the Leaning Tower of Pisa, and had rather primly missed the whole point of it by insisting that the heavier weight would fall a bit faster. Those children devised a beautiful experiment that would have warmed the heart of Galileo himself; it was, in fact, one used first by Galileo's elder contemporary, Stevin of Brussels. They managed a tall ladder from which the two weights could be dropped onto a bit of galvanized iron. The ear (better than the eye) could recognize small differences in the time at which two weights, dropped together, would hit the tin. These Welsh children were treading sacred ground. Most agreed with what they were told was Galileo, and explained away the very small differences they heard; two held out against this conclusion. Their teacher and I agreed that there was no need for us to straighten the whole thing out, at least that day. In his training, he said, he had been told that one should never leave children with wrong conclusions. But he thought children would never hold too strongly to conclusions of their own devising. The danger was that they might uncritically accept the errors that adults so often uncritically impose.

A central argument against the style of science and math education I am suggesting here is that there is no time for it; no time, they say, to reinvent the wheel. I cannot resist a first reply, which is that not everything is known, as yet, about the wheel, either the mathematics of it or the physics. I am thinking of the long and beautiful history, in mathematics and physics, of the circular functions, of the Fourier transformations that use them so elegantly, of the complex domain and the infinite scheme of the roots of unity. I am thinking also of the world of modern physics, in which one may learn to think of rotations that go twice around before getting back to the starting point. Today's children will do well *not* to close their minds prematurely on the subject of wheels.

Past experience must indeed be somehow summarized, must in some way be put in soluble capsules; it cannot be relived in its totality. If we had to relive all past errors and discoveries, it would be a commitment to absurdity. A part—indeed a major part—of the structuring of our minds must come from instruction. But this obvious statement leads much too easily to notions that are, I believe, radically false. *In*struction by a teacher fails without a matching *con*struction by the learner, induction without spontaneity, words without things. The lecture or the textbook passage that succeeds is one that meets an apperception well prepared. When we merely surrender to the textbook, we surrender to defeat.

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What is essential, then, is that children should *often* be instructed, but they should *seldom* be instructed before they are prepared to engage, to criticize, and test at least some small part of what they are being taught. But how does a teacher, knowing such essentials, manage it all? Here, I think, we are most likely to fail. Good teaching is above all a preparation for the unforeseen, for the lovely things that can happen when one has faith that they will happen. When children are optimally involved, they bring to their interpretations of fresh experience a marvelous diversity of understandings from their own past; from what they have recurrently observed and put together and from what they have assimilated from adult associations, all mixed together in ways that are individually diverse but that have a common style. The teachers' job is not to fill some empty places in their minds with new knowledge. The human mind is never empty, though parts of it are often filled without those kinds of large-scale interconnections and reductions-to-order that education should seek to further. The teachers' job is, or should be, to help children sort and rectify. The great teaching art is that of observing and listening, of searching for clues, and of then providing that which may steady and further a budding curiosity, or failing, may lead to further clues. It is as profoundly inductive, in its own way, as children's own learning should be. Teachers, in their own differently ordered minds, can often convict children of error, when in fact, the children's statements are right answers to questions different from those the teachers thought they had asked.

Just here lies the central answer to the critics who impatiently say we have no time to reinvent the wheel, and the right critique of that kind of didacticism to which their thinking tends then to regress. Spoken or written language, isolated from all immediate connection with what it seeks to convey, has little power to excite those resonances in children's minds that can call forth their full powers to retrieve the understandings they already possess and that they can potentially link together in fresh connections and analogies. I quote here a passage from Henry James, used by Frances Hawkins in a broader context, that of a classroom atmosphere in which children of diverse interests and talents can learn well. I use it for the related, but narrower, purpose of suggesting the way in which closely observed natural phenomena can excite early curiosity and understanding. "Small children have many more perceptions than they have terms to translate them; their vision is at any moment much richer, their ap-

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prehension even constantly stronger, than their prompt, their at all producible, vocabulary."[3]

To this elegant statement I would only add a converse. The early-evolved filing systems of children's minds, their resources of memory and analogy and generalization, are often far more readily summoned up by fresh input from activity and observation than by any of those thin verbal streams that well-meaning teachers so often direct at them. What is not within the range of their "at all producible vocabulary" is also not readily excited by a teacher, however produced. The linkage between the closely observed and the thoughtfully stated can only develop well in an informal dialectic, in which what is said, is said in the context of what is seen, and what is seen, is seen in the context of what is said, contexts linked in daily intercourse. If the classroom is bare of the materials and phenomena discussed, this linkage is destroyed. When they are present, the communication between children and teachers can acquire a second and third dimension, indeed an *n*th, which the linear sequence of spoken or written signs can never wholly replace. The phenomena observed in classroom laboratories or field trips become symbols of themselves, so to speak, literal parts of discourse; the talk about them is enriched and informed. Children's grasp of them can be expressed in many ways, in talk, but also in dance sometimes, or painting; the words themselves, of children or teachers, can then be relieved of a freight that alone they cannot bear.

Let me illustrate. The textbook says that heat flows from hot to cold, or that light travels in straight lines, or that the earth goes about the sun; the teacher tries to elucidate, with questions and answers, with drawings, and through other means. But failure is often imminent. In each case, the intended communication is blocked, more often than not, by a radical mismatch between the presuppositions of the book or the teacher and those of the child. What the book and the teacher obedient to it try to communicate often presupposes (but fails to induce) a radical reorganization, in each case, of some commonsense category of experience. If our early grasp of motion is itself all *geo*graphical, then the earth itself surely does not *go*. If our early understanding of light is in contrast with darkness, light may *shine* but not *travel*. Heat may melt the ice or warm the hands, but it is not a flowing kind of thing, a fluid. In all such cases, one must, I think, demand an efficient division of labor between the spontaneous investigations of children and the planning and participation of teachers. When we try to describe the kinds of teaching that contribute suc-

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cessfully to children's reorganization of such big ideas as the earth's motion and the nature of heat and light, we find that the sheer amounts of time involved—time for induction—are large compared to what is usually allotted to them, but also, that the growth of scientific understanding is then overall more rapid. When children can bring their own resources and spontaneous motivation to such learnings, their ability to break fresh ground can be enhanced beyond the range of any of the usual measures.

As for the kinds of phenomena to be brought together with the children and the teacher, there is a rich array, lying on the edge of everyday experience, that children can closely observe. For the beginning study of optics, we can easily provide a wide variety that bring illuminations and shadows center stage. Children (as well as many adults) have a vast background acquaintance; but they have seldom put the lamp, the object, and its shadow in that simple projective relation that has been there all along. It is a bit of geometry that has seldom been closely observed. With lamps and mirrors and pinholes for those strange inverted images, the geometrical abstraction of the light ray is within the reach and grasp of children, though it often takes a great diversity of examples, and some real time, to become compelling. A single classroom demonstration will often miss the point. Taken out of doors, there are new dimensions opened up, among them the daytime astronomy of the sun's motion and the most elegant of all sundials, the classroom terrestrial globe, flooded with sunlight, with its axis pointing to the North Star, and Our Town just on top. We cannot bring the solar system into the classroom, and mechanical models are confusing, because their introduction presupposes the very analogy they are supposed to show. But two string pendulums, hanging near each other, provide a diversity of phenomena that are among the closest terrestrial counterparts of planetary motions. With heavy weights and ceiling or doorway suspensions, their motions are only slowly lost, and they share the style of the heavenly motions, of Newton's sacred laws. Closely observed, they bring to the fore in children's minds a frame of thought very different from the common sense that Galileo and Newton had to overcome in establishing the laws of motion. But again, the phenomenal diversity needed is large, and the times to be spent with such things, in classroom or out, must be generously allotted.

I could spell out a similar story for children's abilities to investigate the phenomena of heat and cold, and for much of the rest of quite elementary science. Most of what we can thus teach—may I please

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still use the word?—has the same quality: it is a quality of playfulness and enjoyment in some of the rich worlds of phenomena that early schooling can provide.

Let me now speak of the very different ambience in which the biological sciences have evolved. Added to the Laboratory of Archimedes, plants and animals import one essential element, which Ronald Colton has repeatedly emphasized: respect for life. The term at first suggests only a detached moral commitment, one alien to the usual amoral stereotypes of science. But looked at closely, the obligations of maintenance are both profoundly moral and, so, instructive. The style of biology, unlike that of the physical sciences, begins with the conditions of maintenance that, over some billions of years, nature herself has supplied. To the usual biological and aesthetic sterility of the classroom, teacher and children must manage to add the necessities of plant and animal maintenance, and must do so with a degree of commitment that is absolute; otherwise they die. Seedlings will grow in the dark, but not for long. What else is needed? Small animals will flourish under conditions that we must try to investigate, and be provided, to that end, with rich environments and choices of food, not just the bland commercial pellets (which will do for a start). Even colonies of bacteria and molds require some conditions of maintenance and care. And finally, again, the field trips are a widening exposure—to the diversities of life, to the ecological web (again, a metaphor from the weaver's art), the flows of matter and energy that sustain us all, the interweaving of context and content without which none of the sciences of life—even molecular biology—would have any proper subject matter; it would have ceased to exist.

Several years ago Frances Hawkins and Ronald Colton offered a course for teachers called "Animals in the Classroom." It was a fascinating enterprise, a trial run of a large subject, one that brought together a great deal of past experience which both had had. The range of animals maintained, or at least investigated, in the course was large, from guinea pigs to hydras. The latter lived in shallow dishes, and managed a living from another species, brine shrimp. The guinea pigs were benignly vegetarian, consuming lettuce and carrots from supermarket sources but, more educatively, the grass that was grown on their premises: seeds of wheat and rye and barley grown in their own territory, a large open steamer trunk of vintage 1910, filled with potting soil and peat moss, with rocks and logs and growing plants. They could have left their Eden, but they never did. There had been other ventures of this sort, such as a large and beautiful cage, in

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a Head Start classroom, for small mice, odor-free when the soil under their feet had the right bacteria and the living area per mouse was large enough. Out of this collaboration, between two teachers who shared a deep understanding of the worlds of children and of other living things, there grew an analogy of proportions: only a good classroom, a good world for children, could sustain and care for a good world within it for small animals. Otherwise there would be only a surface interest, then indifference and neglect.

It is just here, I believe, that one can see the ways in which a good early education at the roots of science and math can nurture the concern for human affairs generally, for the arts and humanities. What I began to describe as the Laboratory of Archimedes has now grown, as it must, into a small human world linked in many ways to the large world of nature, but also to that of human affairs. Out of doors, in the schoolyard and beyond, is an environment rich in subject matter, man-made and natural, open to investigation. The town has a history, accessible from many starting points. Once, that I know of, the search began with a map of children's routes to school, then broadened to its valley and river, an older route to the sea.[4] It could as well begin with a map of ancestry, where each was born, then the birthplaces of parents and even grandparents. And the library corner can hold, for a time, good children's literature of history, of fiction and fantasy, as well as sober science, all sources for the enlargement of acquaintance and imagination. Craft work with yarn and clay and other materials is often relegated to spare time, but can be brought center stage through its relations to history and technology, to the stuffs and arts of everyday life, as well as to science and mathematics.

In all such children's work, guided by thoughtful and responsive teachers, there is a spirit of play. The adult conception of play is usually a stereotypic one: enjoyable activity devoted to no single or sober or serious end, and often disparaged for that reason. I think this definition of play is in fact a good one, but the disparagement is unwarranted. Children's play, closely observed and then steadied and extended by adult provisioning, represents a powerful organizer of their growing experience and, at the same time, a synoptic expression of it; it is an expression that is the precursor of all the established arts, wider in its range and never lost among those who grow creatively into the traditions that those arts represent.[5] But it is also the matrix out of which is born the capacity for the very definition of sober and serious ends, and the capacity to reconstruct them in the

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course of a worthy life. It is the unifying sphere in which all the major capacities of the mind are brought together in some potentially fruitful relation. In the *Critique of Judgment*, Immanuel Kant[6] defined the aesthetic domain by reference to what he called "the free play of understanding and imagination," unfettered by the strict disciplines of cognition or the commitments of conduct. The bachelor sage of Königsberg never explicitly included childhood within the range of his critical philosophy (as Rousseau tried later to do), but his analysis of the role of the arts required a conception of *play* that could have led him there.

I trust that my sketch of a classroom-laboratory-library-atelier is not taken to be giving some temporal priority to math and science, as though it would be expanded stepwise to include the other components only later in the game. There have been many good teachers whose work included nothing of math and science, at least nothing so called or so recognized. There have always been, and must remain, many pathways into the wider worlds of education suited to the special talents of teachers and of children. Good teachers differ more among themselves, and from themselves year by year, than do those who offer a meager fare. The universals of good teaching are invariants across a wide range of surface diversity. Bad teaching is more uniform and more easily described and condemned, and in recent times, we have had a spate of that sort of protest literature.

My argument for the importance of early math and science involves, then, only two logical steps. The first is the recognition that the doorways into these disciplines from the predisciplinary world of childhood are more widely accessible than others. The second is that in creating a school environment in which some of these doors are opened, teachers can evolve a penumbra and a style of inquiry that opens many other doors as well. To create such an atmosphere it is necessary—though by no means sufficient—to stock that classroom with diverse materials that exemplify or generate a wide range of natural phenomena in order to legitimate and invite children's curiosity. Printed paper, mass produced, is cheap and thin, and in its proper subordinate place, essential. It can never transmit more than a small—if necessary—part for the equations of understanding, even for adults. Yet if you conduct a census of materials in most of our classrooms (empty, on a Saturday morning), you find little else.

The classroom paper I despair of is not that of children's literature, too rarely present. Nor is it the vehicle of their written stories and journals, their early engagement with the disciplines of poetry and

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prose. If a classroom has two doors to a hallway, it should have a third, at least, a "lion door"—so a young friend once called it. The well-husbanded library corner, linked to the writing tablet and to a teacher-critic prepared to applaud and to question, can become a lion door. If nature closely observed can first extend children's "at all producible vocabulary," then the written language itself, closely observed and well used, can in turn extend the range of their perceptions. These extensions can reach in all the directions of experience, not least the scientific. And among the scientific extensions, not least is that of size and scale and complexity, which we represent, in shorthand, by the formal written code of the powers of ten. The dough of puff pastry is buttered, folded over, and rolled out repeatedly. Seven foldings make a flaky pastry. How many powers of two (or ten) to reach the thickness of an atom?

There is, then, an added, third step to my argument, which I venture to make in closing it. This step is one that bears on the need for fresh blood in the sciences and for a more informed citizenry, but which also extends the definition of those needs. On the one hand, the evolution of science since the sixteenth and seventeenth centuries has transformed our working relations with nature and has brought us, as a single biological species, to dominate—but also to destablize—the whole of our planetary world. We can learn to love it as a potential Second Garden or, by the turn of the screw, destroy it, and with it, ourselves. The love cannot come as a belated afterthought; it must begin in our early years with the onset of knowledge and wonder, of nature closely observed, observed first in detail and later conceived in powerful generality. Such love has always been a motivating force in scientific investigation, but it can get short-circuited in the pursuit of clever technologies, or is tolerated, in the halls of industry, as a useful eccentricity.

Yet the whole development of science, however motivated, has transformed for us any acceptable understanding of man's place in nature, and thus the framework within which we can adequately form or conceive our own ends and means. In these three or four centuries, our knowledge of the natural world has been extended upward and downward, in the scale of sizes, from the atoms to the cosmos. Begun in speculation, it was vivified by the microscope and telescope, radical extensions of our senses. The first major poet of this extension, awed and frightened by its implications, was Blaise Pascal, contemporary of Newton and of Leeuwenhoek. Pascal was a mathematician and physicist, abreast of, and contributing to, all

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those early developments of science. He was also one of profound ethical and religious commitment, who saw that nature, in its vastness, could no longer be regarded as only a set of theatre props for the medieval Christian domestic struggle of good and evil. Another contemporary, Baruch Spinoza, was equally involved in, and affected by, the new world of science. Christian and Jew, both faced with the vision of infinite nature, concluded that man's whole dignity lies in the power of thought: the thinking reed can achieve some comprehension of the power of nature and of man's place. Pascal dramatized the uniqueness of man, while Spinoza sought to understand it as a mode of nature's own self-comprehension. But both acknowledged the new vision of science as a turning point for ethics and for religion.

Today we can add a new dimension to that vision that fills it out and makes its import still more compelling. To the vast scale of size we can add the scale of historical time, a scale unknown and hardly guessed in the seventeenth century. In size we are almost half-way between the greatest thing we know and the smallest, as Pascal announced. More precisely, we are twenty-five powers of ten above the smallest things we know, and sixteen powers of ten below the largest.[7] In time, the scale is almost as great, from the briefest possible subatomic events to the duration of the cosmos in its now-estimated history. The duration of our own human least awareness is some twenty powers of ten above the subatomic minimum, while that of a human generation goes up by about nine further powers of ten. The duration of our species is about a hundred thousand of these generations, five powers of ten. For the duration of terrestrial life as a whole, we must multiply again by a thousand, the third power. On this scale, the earth itself, and then the whole cosmos, is less than ten times older, a single power of ten. If our dignity lies in the power of thought, as Pascal said, it is matched by a dignity of age; we and all our cousins in the terrestrial living world, though middling on the scale of sizes, are almost as ancient as the cosmos itself.

To have a sense for all these numbers, and the rich scientific story from which they are distilled, will surely suffice us not at all in baking bread or in coping with the destruction of our farmlands or the pollution of city slums. It will not of itself avert the peril of nuclear war, that terrifying stepchild of scientific advance. Nevertheless, we need that story as a framework for understanding, a framework that allows us first to acknowledge the issues that face us today, and then to work to understand and meet them. What we desperately need are

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the powers to cultivate the imagination far beyond the limits of everyday parochial life, and these surely include a sense for the many powers of ten. Our parish, our pueblo, our shamba—the neighborhood of each of us—has grown by many such powers, in space and in history, whether we know it or not. We need six powers of ten to understand the difference between a chemical explosive and a nuclear bomb; that is something even our great leaders, and the constituencies that elect them, have not yet adequately grasped. We need several powers of ten to frame the difference, in our imaginations, between our own years—six or ten or sixty—and those of the rocks we scramble over on a field trip or holiday. Again, it is six powers of ten to go from the perimeter of our school grounds to the distance to the moon, and a few more to span the distance to the sun. And so it goes, for the distance to the nearest star, then to Andromeda, and finally to the edges of the early universe. So it goes also to the distant past, in which we can see that all living things under the sun are cousins and all men are brothers.

As a final step, I wish to acknowledge a second sort of argument against much that I have said and against the optimism implicit in it. It is an argument that will rise most cogently in the minds of those wise in the ways of our present-day schools, and I must acknowledge it fully. I began with an emphasis on the continuity of culture, whether marvelous or dreadful or only drearily predictable, a continuity that is unavoidable in all our educative associations—and the schools are no exception. This argument is very simple: the educative potential of our schools is not high enough, and will not foreseeably rise high enough, to warrant any implicit optimism. To have such good education, except here and there and almost by chance, implies the existence of teachers who are themselves the products *of* that very education; while in fact the teachers we mainly produce are poorly educated. They are poorly educated with respect to subject matter, first of all. They are poorly educated with respect to the patterns of human development and the arts that foster it. And they are enchained within a school bureaucracy that has not learned to treat them as professionals in need of professional support and capable of a fully professional independence and accountability. They are treated rather as civil servants of a low grade, and the treatment is all too often self-confirming. In short, there is no way visible in which the antecedents of what we need can be matched to the consequents of what we have. So goes the argument of the critics.

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Two decades ago, indeed, many of those who sought to improve our education in science and math were given to a false optimism, based on the belief that the curriculum reforms then fashionable would be so potent that their effects would somehow bypass the inadequate education of teachers. This was an unjustifiable arrogance, and time has shown it to be so. The good consequences of those efforts lay mainly in those cases where teachers themselves became deeply involved in the reforms and showed us how to reduce them to practice. Help from the outside is of no avail unless, and in the measure that, it contributes to the growth and stature of the teachers, and they in turn contribute. That should be held to, I believe, as a firm axiom. We should judge all new proposals by it, whether for texts or guides or computer modules.

The continuity, then, is unavoidable, as is a certain pessimism concerning the probability of significant reforms. The optimism that many of us feel, the sense of romance about the potentialities of early education, is an optimism of the possible, not one of somehow calculable probabilities. But, I respond, possibility can be robust. Those of us who have been fortunate enough to sniff out and find the good classrooms, variations on the sorts of themes I have been suggesting, have indeed found them, though rarely enough—have found them, reduced to practice and thriving, guided by quite bona fide mortals, overworked but happy in their craft. And here, too, there is continuity. Almost always in the background or foreground of these teachers there is some strong educative influence, some professional support that they have assimilated and modified, perhaps extended. No one person invented the wheel or the telescope or the internal combustion engine. They have been evolved, step by step, without any violation of continuity. And so can good education, though it is far more complex. The Law of Continuity is no warrant for fatalism.

In the biological world, there is a kind of theorem about the emergence of new types and new species: they do not arise by sudden or massive modification of older and dominant species, but appear, rather, because some genetic variety, initially rare, manages to grow at a rate faster than others around it when a new ecological niche appears that favors it. That is why evolution is not predictable; it works through the amplification of initially rare varieties that early go unnoticed. Good ideas have that kind of history, too, and so we often see it only in retrospect. I should hope that we begin to think of the improvement of education in just these terms. If good patterns of work with young children can be recognized early, while they are—

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as indeed they are—still rare and all too easily lost, we can hope to create for them some systems of protection, of support, and of growth. Since they are rare, the initial investment is moderate, and it can grow with the success it increasingly demonstrates. In our own search for the good sorts of early educational patterns, we have found them very unevenly distributed. Where they have been thickest on the ground, we have found such systems of professional support and encouragement, working high above the average level of what is called in-service education or staff development, usually a perfunctory service with marginal budgets that can be most easily lopped off in hard times. To say this is not an expression of pessimism, but of outrage.

The continuing education and professional growth of our teachers is of course not the only way of modifying the loop of continuity from teacher inadequately educated to children poorly taught. There are others, especially those affecting the pre-service education of teachers. Here it is customary to blame the schools of education, themselves inadequately provided for serious professional training. They are, to be sure, responsible for some part of the failure. But a large part of the blame should be laid at the feet of our undergraduate arts and sciences colleges, which fail conspicuously to provide rich fare for future teachers of the young. Such students especially need what all college students could profit from, a wide and liberal exposure to the riches of genuinely elementary subject matter. This kind of provisioning is typically sacrificed to a pattern that leads as quickly as possible to advanced subject matter of sorts that have little relevance to the teaching of the young. With honorable exceptions here and there, mathematics and science are especially subject to this criticism. Future teachers are typically required to complete one or two courses, of which the content is regarded as so elementary as to be beneath the dignity of college lecturers; still formal in style, they are thin in content. Often those who teach such courses are themselves unfamiliar with the elementary riches of their own subject matter, and a typical course in the number system, or in remedial algebra, has little relevance to the needs or to the intellectual capacities—often substantial—of students bound for careers as teachers of the young. Knowing nothing of its enticements they have often been turned off by such subject matter, and we do very little indeed to meet the challenge. Again the treatment we provide is self-confirming: if they were any good, it is said, they would go into some more prestigious vocation.

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The same pattern is visible in the sciences, with the same honorable but all-too-rare exceptions: Physics is taught mainly for future physicists, chemistry for those who might, with one chance in forty, become chemists, biology for future biologists, and so on. The upward draft, what physicists should recognize as an academic chimney effect, is very powerful, and not easily counteracted by the efforts of those few who have insisted on a wider view of their own professional commitments.

In all early education, then, the part played by the teacher is central and critical. It can be ameliorated by the enrichment of several kinds of support now on the whole very poorly provided, but only in the measure of its contribution to teachers' own continuing professional education, their growth of skill and insight, their morale. I believe we should accept this proposition as central and critical to the theory of early education. It can be derived from wide ranges of evidence; in the formulation of theory, it should be treated as an incontrovertible starting point. I have called it an axiom. In the history of mathematics, the word *axiom* came to mean an unquestionable truth, from which others could be derived. Later it was bled of that meaning and stood only for some arbitrary logical starting point, a hypothesis whose contradictory could also be a starting point for some alternative logical theory. The original meaning of the word is, I think, more useful than either of these. In that meaning, an axiom is a proposition most highly valued (ἀξίωμα, a thing valued), and thus the last to be questioned in any further investigation.

When the central importance of the teacher is accepted as axiomatic, it provides a strong criterion in judging any proposed educational reforms. Thus curriculum development that robs teachers of opportunities for developing their own curricula, imaginatively matched to their children and their circumstances, should be weighed as negligible or negative. The sort of curriculum development that contributes to teachers' own critical and inventive powers should be supported; that which purports to replace their powers of invention with a dismal array of daily guides geared to dull texts and readers, and those endless workbooks that destroy all zeal for reading or expression—those should be destroyed. No ban against book burning should protect them.

In the hands of children and under their inventive guidance, the classroom computer can add more than one dimension to a teacher's repertoire—as a glorified scratch pad for extending children's powers, as an *n*-dimensional kind of book, and as a sheer (though for

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some, powerfully addictive) delight in fun and games, sometimes educationally worthy. In its cheapest and now best-advertised programs, it robs the teacher of vital initiatives, and if our axiom is seriously meant, should be condemned. This does not exclude all routine uses, such as foreign language practice, review of some imaginative arithmetic and geometry of the Pythagorean genre, or as a challenge to skill in estimation of numbers very large and very small. But because the computer is literally infinite in its potentialities, it can create the illusion that it is the real world, safely confined by the keyboard or even, in expensive versions, the light pencil. Einstein said that God is subtle but not malicious. We should add that commercial programmers are seldom malicious but never, in principle, divinely subtle. They are never even as subtle as teachers who know their particular children and guide them well. I quoted earlier the theorem that well-cared-for animals are possible only in a well-cared-for classroom. In the same spirit it should be added that a computer in the classroom can be well used only if there are other enticements there that will fully compete with its attractions. Much of its perceived addictiveness is only an escape from boredom. We should be thankful that there are such escapes, but there should be many more. The stuff for which computers can be well used, seldom discussed, is an abstract from the close observation of natural and human affairs; otherwise, they give us only another turn of the screw.

But there are other and more powerful conclusions from our axiom, and the chief of these is that teachers should by all means endlessly educate themselves in the substance of their craft and be well-trained in its practice. The substance is to be found in the wide range of elementary subject matter accessible to children, from which teachers can, over the years, evolve increasing and impressive repertoires. The practice contributes as it is reflected upon and collegially examined, alone and with others, in the context of professional curiosity about human learning and development. And all of this—I repeat—implies levels of professional support, pre-service and in-service, that we are as yet very far from providing.

The cadres who can support such growth are, then, the key. They may not now be numerous, but they are more numerous than our present readiness to enlist and honor them will admit. It is an encouraging fact that in recent years their ranks have been filled by increasing numbers who have come from such disciplines as mathematics or physics, willing to learn about children and about teaching them, and who believe that their own professions should be expanded to in-

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clude such commitments. There are also many successful teachers who can be persuaded to spend some time, at least, in others' classrooms. Coming from varied backgrounds and able to learn from each other, such cadres can over time become a powerful agency of improvement in early schooling. Working through the colleges of education, they can guide beginners to good classrooms for serious apprenticeship. Working in the schools themselves, they can give personal support to teachers who seek it. Through workshops and seminars, they can bring to the schools something of the atmosphere of a learned society, the nourishment and morale of professional work and talk.

The secret of this whole process is a working association that is essentially personal, mainly one to one or to a few. As in the classroom for children, books and pamphlets and research reports can help, but only as supplements. Teaching as an art can be reduced to practice primarily with the help of others already skilled in it. Unfortunately, our schools of education have retreated more and more to a world remote from classrooms of the young, and those who spend much time there in violation of this tendency are typically less honored than those who publish many little papers. Even fewer and less honored departmentally are those who regularly visit from departments of math or physics, history or literature, though it might teach them more about college students. We have evolved an academic pecking order in which such ventures are vaguely demeaning. We might all learn more if we reversed it or at least gave serious support to interesting deviations from it. Even our public school systems are guilty, in the main, of a similar retreat. Principals used to be selected as principal teachers, the most skilled and successful, able to help those who worked under them. If the selection was not always wise, the criterion was. Supervisors and consultants and specialists have always been available in principle, though in times of tightened budgets, their ranks have mostly been depleted—unless their work has shifted to a more bureaucratic role invisible to the teachers they should be available to. Yet all of the professional support I have been speaking of is little more than a percent or so of the budgets from which they are now so frequently excised. Such budgets, of course, are not decisive, only necessary. What counts is the quality of professional support we offer to our now-neglected teachers, and that is where all of our discussion, of early math and science, and of all else in the curriculum, should come to a final and practical focus.

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To start with the best we already know, toward a new species of early education, is to start small, putting the most effort where we find the greatest readiness for growth. This is unfortunately not a precept that fits our current fashionable notions of cost-effectiveness. To trim quantity to quality is often regarded as elitist, but it is not—not if it aims at growth. Some of our colleagues in these efforts, here and abroad, have deliberately sought out promising beginnings where the going is hardest, in the schools of city slums or regions of rural poverty. The work is harder there, but success is more conspicuous. That is surely not elitist. On the other hand, cost-effectiveness will usually be measured by some average changes (in test scores and the like), and in the early stages these will be buried in the numbers, the tyranny of the arithmetic mean. From this point of view, a long-term commitment of the sort we all might otherwise support is hard to justify. From small beginnings, the growth, in early stages, will always be buried in the sea of statistical noise. What can accrue over some years of growth is another matter, and that seems to require an act of faith, as indeed it does. Growth can follow the exponential curve for a good time at least, and before long will overtake all that begin large and, of necessity, are mediocre. And if faith cannot be justified by short-term statistics, it is all the more important that it be supported by knowledge. I have urged that we possess this support, that it lies in the axiom of the centrality of our teachers' own professional and human needs, now poorly met.

ENDNOTES

[1]See Edwin Herbert Lewis, "What a Linguistic Contextualist Thinks of Philosophy," *Outlook* no. 20, Summer 1976 (Boulder, Colorado).

[2]David Hawkins, "What it Means to Teach," *Teachers' College Record*. Teachers' College, Columbia University, New York, Spring 1973.

[3]*What Maisie Knew* (New York: Penguin Books, 1974), p. 7. Frances Hawkins's discussion is in "The Eye of the Beholder," in *Special Education and Development: Perspectives on Young Children with Special Needs,* edited by S. Meisels (Baltimore: University Park Press, 1980).

[4]A classic account of such work in physical and human geography is Lucy Sprague Mitchell, *Young Geographers* (New York: John Day, 1934).

[5]See Michael Armstrong, *Closely Observed Children* (Richmond, Surrey, England: Chamelion Press, 1980). See also a fine new translation of *Tolstoy on Education,* selected and edited by Alan Pinch and Michael Armstrong (East Brunswick, New Jersey: Associated University Presses, 1982).

[6]Immanuel Kant, *Critique of Judgment* (New York: 1952). See also John Dewey's *Art as Experience* (New York: 1934). Dewey is more Kantian here than he was willing to acknowledge.

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[7]These powers of ten are from *Powers of Ten,* by Philip and Phylis Morrison and The Office of Charles and Ray Eames (New York: Scientific American Library, 1982). The book is based on a film of Charles Eames of the same title, which in turn was inspired by an earlier small book, *for children,* by a Dutch schoolteacher, Kees Boeke, *Cosmic View: The Universe in Forty Jumps.*

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A.B. Arons

Achieving Wider Scientific Literacy

THAT THE PUBLIC UNDERSTANDING OF SCIENCE, or scientific literacy, is in a lamentable state is an old story. Magazine articles, educational literature, and pronouncements of scientific associations all through this century and well back into the last bear testimony to this. Scientists of several decades ago, returning to academic work after time spent in research or serving in World War II, were particularly determined to help college students acquire a better sense of the nature, power, and limitations of scientific thought, as well as a better understanding of the interactions between science and society. Since then, the escalating impact of science and technology on moral, ethical, political, and societal problems has only continued to enhance the urgency of the problem of education and to heighten the pertinence of the liberal education objective.

For years, the meetings of scientific societies reverberated, and pages of educational journals were filled, with descriptions of new courses that had been designed to lead nonscience majors to greater scientific literacy. Almost every report presented or published was accompanied by the results of "evaluations" of student answers to tendentious questionnaires, the answers invariably demonstrating how much the students loved the course, valued the learning experience, and appreciated the instructor's efforts on their behalf. With but a few exceptions, these courses vanished and were rapidly succeeded by "more up-to-date" but essentially identical—and equally evanescent—versions, also accompanied by enthusiastic student testimonials.[1]

These numerous attempts have had very little impact on scientific literacy. Those who were students in such courses, and responded so favorably on the questionnaires, show little or no understanding of

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science and of its interactions with society. In retrospect, most say that they enjoyed the courses very much, but recall nothing of what they were supposed to have learned. (It has been sardonically suggested that, this being the almost universal outcome, perhaps we should direct our efforts toward devising courses still more enjoyable and still easier to forget.) Yet the clamor for making science a more effective component of liberal education continues unabated, and with an urgency that indicates how little past efforts have achieved.

The notion that the understanding of science can be achieved by purely verbal inculcation seems to me to be a principal source of failure. Experience makes it increasingly clear that verbal presentations—lecturing to large groups of intellectually passive students and having them read text material—leave virtually nothing in the student's mind that is permanent or significant. Much less do they help the student attain what I consider the marks of a scientifically literate person.

Since these attributes underlie my contentions and recommendations in this paper, it might be well at this point to enumerate them. The person who has acquired scientific literacy will possess the ability to:

1. Recognize that scientific concepts (e.g., velocity, acceleration, force, energy, electrical charge, gravitational and inertial mass) are invented or created by acts of human intelligence and imagination and are not tangible objects accidentally discovered, like a fossil, a new plant, or a particular mineral.

2. Recognize that to be understood and correctly used, such terms require careful operational definition, rooted in shared experience and in simpler words previously defined; to comprehend, in other words, that a scientific concept involves an idea first and a name afterward, and that understanding does not reside in the technical terms themselves.

3. Comprehend the distinction between observation and inference, and to discriminate between the two processes in the scientific context under consideration.

4. Distinguish between the occasional role of accidental discovery in scientific investigation and the deliberate strategy of forming and testing hypotheses.

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5. Understand the meaning of the word "theory" in the scientific domain, and to have some sense, through specific examples, of how theories are formed, tested, validated, and accorded provisional acceptance; to recognize, in consequence, that the term does *not* refer to any and every personal opinion or unsubstantiated notion and thus, for example, to see through the creationist locution that describes evolution as "merely a theory."

6. Discriminate, on the one hand, between acceptance of asserted and unverified end results, models, or conclusions, and on the other, understand their basis and origin; that is, to recognize when questions such as "How do we know . . . ? Why do we believe . . . ? What is the evidence for . . . ?" have been addressed, answered, and understood, and when something is being taken on faith.

7. Understand, again through specific examples, the sense in which scientific concepts and theories are mutable and provisional rather than final and unalterable, and to perceive the way in which such structures are continually refined and sharpened by processes of successive approximation.

8. Comprehend the limitations inherent in scientific inquiry and be aware of the kinds of questions that are neither asked nor answered.

9. Develop enough basic knowledge and understanding in some area (or areas) of interest to allow intelligent reading and subsequent learning without formal instruction.

10. Be aware of at least a few specific instances in which scientific knowledge has had direct impact on intellectual history and on one's own view of the nature of the universe and of the human condition within it.

11. Be aware of at least a few specific instances of interaction between science and society on moral, ethical, and sociological planes.

12. Be aware of very close analogies between certain modes of thought in natural science and in other disciplines such as history, economics, sociology, and political science; for example, forming concepts, testing hypotheses, discriminating between observation and inference, constructing models, and doing hypothetico-deductive reasoning.

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The list is neither exhaustive nor prescriptive. It illustrates some of the insights that I believe characterize scientific literacy and that I find most college undergraduates, given the time and opportunity, and having the willingness to exert some intellectual effort, can encompass. Readers will no doubt have valid modifications, preferences, and priorities of their own. These can be interpolated and examined in the light of the following discussion, which I will confine to efforts being made through instruction in schools, colleges, and universities to upgrade scientific literacy.

To develop a genuine understanding of concepts and theories, the college student, no less than the elementary schoolchild,[2] must engage in intense deductive and inductive mental activity coupled with interpretation of personal observation and experiences. Unfortunately, such activity takes place in only a handful of passive listeners, but it can be enhanced, nurtured, and developed in the majority, provided it is experientially rooted and not too rapidly paced.[3]

Researchers in cognitive development describe two principal classes of knowledge: figurative, or declarative; and operative, or procedural.[4] Declarative knowledge consists of knowing "facts"; for example, that the earth revolves around the sun, that matter is composed of discrete atoms and molecules, that animals breathe in oxygen and expel carbon dioxide. Operative knowledge involves understanding the source of such declarative knowledge (How do we know the earth revolves around the sun and why do we accept this view when appearances suggest the reverse? What is the evidence that the structure of matter is discrete rather than continuous? What do we mean by "oxygen" and "carbon dioxide"? How do we recognize these as different substances?) and the capacity to use, apply, transform, or recognize the relevance of the declarative knowledge in new or unfamiliar situations.

There is increasing evidence that our secondary schools and colleges are not doing a very good job of cultivating operative knowledge in *any* of the formal disciplines and that the teaching of science is not unique in this respect—although the failure there is more immediately obvious.[5] Let me draw on some specific illustrations from my own experience. Virtually any individual will tell you that the earth and the other planets in our solar system revolve around the sun. To many, there is nothing paradoxical about this because, unlike the ancients, few people now have occasion to watch the sky and be directly aware of the motions to be observed. If asked for the evi-

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dence and reasons why they accept the notion of a heliocentric system, the vast majority of individuals react only with dismay or embarrassment; some mutter something memorized and unintelligible about stellar parallax. Having accepted what Whitehead called an inert end result received from Authority, they have nothing but declarative knowledge, and no understanding of the first grand synthesis provided by modern science. They are probably even less sophisticated than their medieval counterparts, who would have cited the geocentric model but would have qualified it as only "saving the appearances" rather than representing final Truth. Such modern-day reactions are typical with respect to many other aspects of science, and, I submit, are not what we have in mind when we speak of "an understanding of science."

Another example is drawn from experience with in-service teachers in summer institutes and with pre-service teachers in undergraduate science courses (the two groups turn out to be indistinguishable in their levels of understanding of science subject matter). Somewhere in their school experience or in other circumstances, they all heard expositions about "electrical circuits," saw diagrams of electrical configurations in books and on chalkboards, and listened to assertions of the facts and concepts of current electricity.

When both groups are given a dry cell, a length of wire, and a flashlight bulb, and are asked to light the bulb, they almost invariably start by connecting the end of the wire to one terminal of the battery and holding the bottom of the bulb to the other end of the wire, or they connect the wire across the terminals of the battery and hold the bottom of the bulb to one battery terminal. They have no sense of the two-endedness of either the battery or the bulb; few of them notice that the wire gets hot when connected across the battery terminals, and almost none infers anything from the observation. It takes them twenty to thirty minutes to discover, by trial and error, a configuration that lights the bulb. Seven-year-old children, when confronted with the same situation, go through the sequence exactly, and at the same pace. Absent the synthesis of actual experience into the concept of "electrical circuit," the college students, despite the words they "know" and the assertions and descriptions they have heard, have no more understanding of the ideas involved than the seven-year-old approaching the phenomena *de novo*. Purely verbal inculcation has left essentially no trace of knowledge or understanding. Such is the outcome of the majority of our present modes of instruction.

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College courses that purport to cultivate scientific literacy in the nonscience major fall into two principal classes: courses that in one quarter, one semester, or even one year attempt to give students an insight into the major achievements of a science (e.g., in physics, everything from Galileo and Newton through the laws of thermodynamics, relativity, and quantum mechanics); and courses that focus on some narrower topical area such as the energy crisis, spoliation of the environment, the application of science to military problems, ethical and moral questions lying behind modern advances in molecular biology, philosophical questions posed by relativity and quantum mechanics, and so on.

The courses in the first category have been invented and reinvented in essentially unchanged form countless times. Despite pretensions to being substantive and not merely "survey courses," and despite the always-glowing student "evaluations," these courses have had so short a half-life, and so little effect on the generations of students subjected to them, that they are still being reinvented to fill the persisting vacuum. Young scientists seem to think the vacuum is there because this mode has never been tried before, and that the solution lies in presenting the material in their own particular, enthusiastic, and impeccably lucid way. The truth is that the vacuum is there because the mode is completely without educational success, yet its proponents continue to justify it on the ground that the students are given a "feeling" for the content of science and the nature of modern scientific thought.

Such efforts founder—as their replications surely will—first because they invariably subject students to an incomprehensible stream of technical jargon that is not rooted in any experience accessible to the student; second, because the material is presented much too rapidly and in far too great a volume for any significant understanding of ideas, concepts, or theories to be assimilated. The pace makes difficult, if not impossible, the development of any sense of how concepts and theories originate, how they come to be validated and accepted, and how they connect with experience and reveal relations among seemingly disparate phenomena; and both pace and the volume of material preclude any meaningful reflection on the scope and limitations of scientific knowledge or of its impact on our intellectual heritage and view of man's place in the universe. The "stream of words" courses have not solved, and will not solve, our education problem, however handsomely illustrated the texts and however lib-

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erally salted they may be with allusions to pollution, ethics, energy crises, stellar nucleosynthesis, black holes, and Kafka.

The courses in the second category, although supposedly narrower in scope, suffer from related difficulties. It seems to me that intellectual integrity would demand that students acquire some genuine comprehension of the scientific concepts, theories, and insights underlying the great topical problem being examined, and that students should not be encouraged to discourse vacuously on matters they essentially do not understand. With students who already have the requisite background, one can, of course, enter these discussions directly. But with students who have no notion of what "energy" means (many regard it as a material substance) and have formed no awareness of the multiplicity of interactions leading to the restrictions embodied in the laws of thermodynamics; with students who have no basis for belief in the discreteness of the structure of matter (knowing only a string of names such as "atom," "molecule," "nucleus," "electron" that have been thrown at them by assertion, and without having examined any of the experiential evidence and reasoning underlying the names); with students who have no idea what is meant by electrical charge or of the grounds on which we accept the proposition that the earth revolves around the sun; and with students who are still Aristotelian in their use of teleological locutions and in their unawareness of the law of inertia—with such students it is intellectually specious and dishonest to pursue the initial discussion without first helping them to form and thoroughly understand the essential prior concepts. Indeed, once they see where intellectual integrity lies and what it is they must understand in order to talk meaningfully and intelligently about the original problem, few students will object to doing this.

Such backtracking to the necessary scientific understanding, however, drastically reduces the amount of course material that can be covered. To my knowledge, very few such courses have made the sacrifice, and the students emerge with no more understanding of scientific concepts or of the nature and limitations of scientific thought than do the victims of courses in category one.

What is the alternative? I think it is essential to back off, to slow up, cover less, and give students a chance to follow and absorb the development of a small number of major scientific ideas, at a volume and pace that make their knowledge operative rather than declarative. Depending on the time available, they might, for example, be led through one or more of the following questions:

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1. Why do we believe the earth revolves around the sun? In what context of concept and theory is this statement "true"?

2. Why do we believe that matter is discrete in structure; that is, what is the evidence for the atomic-molecular theory?

3. What do we mean by the concept "electrical charge"? How does the concept originate? Is "charge" a kind of substance? On what grounds do we believe that there are only two kinds of electrical charge? What (hypothetical) experience would force us to conclude we had discovered a third variety?

4. Why do we believe that atoms have discrete structure on a subatomic scale? What are some simple, intelligible pieces of evidence? (Bland assertion of the existence of an entity named "electron" is not evidence of anything at all; yet much teaching is done in this style.)

5. What experiences lead to and reinforce the creation of the concept "electron"? What is the evidence that such an entity is a universal constituent of matter? What is the evidence that it has subatomic mass?

In contrast, I suggest that the following are essentially useless and may possibly be counterproductive:

1. Students being told about the "fascinating" particles of high-energy physics, with jargon about interactions, angular momentum, mass-energy relations, quantum transitions, and the uncertainty principle, when they have no conception of what is meant by velocity, acceleration, force, mass, energy, or electrical charge, much less of how we obtain evidence regarding the structure of matter on a scale that transcends our sense perceptions.

2. Students who are still essentially Aristotelian, with no significant understanding of the law of inertia, being invited to toss around phraseology about Coriolis effects in meteorology and oceanography.

3. Students who have no notion how to define local noon, midnight, or the north-south direction, who have no idea of the origin of the seasons or the phases of the moon (believing the unilluminated part of the moon to be the earth's shadow), and who are unaware that the stars have a diurnal motion, being subjected to lectures on stellar nucleosynthesis, quasars, pulsars, and black holes, in courses called "Astronomy."

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4. Students conned into reading and talking about DNA, the molecular structure of genes, and nerve and muscle action, when they have no idea why we believe in atoms and molecules; how we come to know anything about molecular formulas, size, or structure; what is meant operationally by "oxygen," "nitrogen," and "carbon"; and what is meant by "electrical charge" or "potential difference," and how we know that these concepts have anything to do with nerve action.

ILLUSTRATING THE NATURE OF SCIENTIFIC THOUGHT

By addressing ideas such as those suggested in the preceding section, at a pace that allows understanding of the concepts and consideration of the "How do we know . . . ? Why do we believe . . . ?" questions, illustrations of the character and limitations of scientific thought, rather then being injected artificially by assertion, will arise naturally and abundantly. Consider the following examples.

When, in the *Two New Sciences,* Galileo confronts the problem of describing the change in the velocity of a moving body (the idea to which we give the name "acceleration"), he points out that there are at least two alternatives: (1) we observe that the object changes its velocity from one value to another while it traverses a distance of so many cubits, and we might then elect to describe this motion by means of the number that indicates how much the velocity changed for each successive cubit of displacement; (2) the same velocity change, however, occurs over a measurable interval of time, and one might also characterize the process by the number that indicates how much the velocity changes in each successive second. Which mode of description should be adopted? The choice is not trivial.

Galileo selects the second concept: change of velocity per unit time. His objective is to create a description of "naturally accelerated" motion (free fall), and he has a deep intuitive conviction that free fall is *uniformly* accelerated in this sense, but not in the sense of change of velocity per cubit of displacement. On the basis of a hypothesis, an inductive guess, he selects the concept that will yield the simplest and most elegant description of free fall, and proceeds to test the hypothesis by deducing consequences that can be tested by experiment.

Here are, lucidly displayed, several significant facets of the scientific enterprise: the roles of inductive and deductive reasoning; the fact that scientific concepts are created by acts of human intelligence

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and are not material objects stumbled over and described by their discoverer, like a new continent or a new animal; that choice may enter into the sequence and that there might be room for aesthetic criteria such as elegance and simplicity.

Here, too, is the new and revolutionary idea of forming an a priori hypothesis and testing its mathematical predictions by experiment. The Greeks had appealed, on at least some occasions, to both observation and experiment (they adduced, for example, the resistance of an inflated animal bladder to compression as experimental evidence for the corporeality of air), but they did not test the models they invented for the explanation of natural phenomena.

I retell this well-known story not to lay claim to new or profound insights into the philosophy and history of science, but only to point explicitly to a set of significant ideas that college students can comprehend and appreciate, ideas that lie just below the surface in any introductory study of physical science, but that students are rarely given the opportunity to discover, articulate, and savor. To discover these insights, students must have the opportunity to stand back and examine what happened, to relive some of the intellectual experience, to analyze and assess the line of thought, recognizing the elements of its logic, its strength, and its limitations.

In very few texts and courses, however, are students afforded this opportunity. The standard definitions of velocity and acceleration are asserted as though they were inevitable, rocklike formations that have existed for all time, while deference is paid to "history" by mention of the name of Galileo and by a few pompous, unsubstantiated clichés about his invention of "the Experimental Method" and his paternity with respect to "Modern Science."

Students can indeed acquire mature and intelligent intellectual perspectives toward the methods, processes, successes, and limitations of science. Such perspectives, however, are not automatically conveyed by training students to calculate how high a stone will go when it is thrown up into the air, or how much a given electrical field will deflect an electron beam. Such intellectual perspectives can be developed only by coupling understanding of the scientific subject matter itself with the insights gained by standing back and examining not just the end results, but what happened in terms of "How do we know . . . ? Why do we believe . . . ?"

Opportunities to make explicit such facets of the cultural phenomenon that is science arise at almost every turn. Consider a few further examples.

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In light of the didactic manner in which scientific concepts are forced on students, it is understandable that they acquire the notion that scientific terms are rigid, unchanging entities with only one absolute significance that the initiated automatically "know" and that the breathless student must acquire in one brain-twisting gulp. It comes as a revelation and a profound relief to many students to learn that scientific terms go through an evolutionary sequence of redefinition, sharpening, and refinement, as one starts at a crude, initial, intuitive level, and profiting from insights gained in successive applications, develops the concept to its later sophistication.

For example, the concept of "force" is legitimately introduced by connection with the primitive, intuitive, muscular sense of push or pull, but in the law of inertia, we redefine it to apply to any effect that imparts acceleration to a material object (for example, the action of an electrically charged rod on bits of paper). We endow completely inanimate objects with the capacity to exert forces on other objects (the charged rod exerting a force on the bits of paper, the table exerting an upward force on the book that rests upon it, the earth exerting a downward force on us—our weight—and an upward force at our feet). Following Newton, we then extend the concept even further and create the idea that when the table exerts an upward force on the book, the book simultaneously exerts a downward force on the table. We have come a very long way indeed from the original use of the word "force" for an animate, muscular push or pull on another object.

Similarly, starting with the crude idea of "velocity" as a measure of how fast (as an average over a finite time interval) an object travels along a straight line, we refine this primitive notion into a concept of instantaneous velocity; we then endow the concept with additional properties of direction in space and with rate of change of both direction and magnitude.

At each stage in this sequence of evolution and redefinition, the original word—its meaning having changed in significant intrinsic ways—no longer denotes only the first intuitive idea to which it was applied, but a new and more sophisticated concept. Modest self-consciousness about the process of definition and redefinition increases enormously the confidence of students in their own grasp of the new sequence of thought, opens their eyes to similar shifts and extensions in the subsequent generation of concepts such as "energy" and "electrical charge," and carries over into other areas of study by alerting them to similar semantic shifts in their social sciences and humanities courses—shifts, I might add, that are rarely pointed out.

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In the courses I teach, I indicate from the first day that we will operate under the slogan "idea first and name afterwards," and that technical terms acquire meaning only through the description of shared experience in words of prior definition. When students try to exhibit their erudition (or take refuge from questioning) by dropping the names of technical terms that have not yet been defined in class, my staff and I go completely blank and appear not to understand what is being said. Students catch onto this quickly. They cease name-dropping, and begin to recognize when they do not understand the meaning of a term. Soon they are telling me that they are getting into trouble in a psychology, a sociology, a political science, or an economics course by asking the instructor for the meaning of technical terms that have been flung at them with great abandon.

This repeated feedback tells me that here is an aspect of intellectual development to which many students break through relatively quickly and easily;[6] it also says quite invidious things about the courses in which the negative experiences occurred.

During the 1830s and 1840s, Michael Faraday's beautiful and elegant experimental investigations of electricity and magnetism caused him to raise some very deep questions about these phenomena, and students can be led to articulate a few of these themselves: Is there a process by which one electrically charged particle exerts a force on another? If one of the particles is suddenly displaced, does a finite time interval elapse before the force on the second changes? Does a finite time interval also elapse between the instant an electric current flows in a wire and the instant a neighboring compass needle begins to swing in response to the magnetic effect of this current? If a finite time interval does elapse in each case, what happens in the intervening space between the interacting objects? To answer these questions, Faraday invented a model, a visualization that completely transcended any direct sense experience—the famous concept of "lines of force," which stretched, contracted, spread apart, and pulled together, propagating electric and magnetic effects through evacuated space—the concept that James Clerk Maxwell subsequently elaborated into the sophisticated modern notion of "field." Faraday wrote almost apologetically about this highly speculative model:

> It is not to be supposed for a moment that speculations of this kind are useless or necessarily hurtful in natural philosophy. They should ever be held as doubtful and liable to error and to change, but they are wonderful aids in the hands of the experimentalist and mathematician; for not only are they useful in rendering the vague idea more clear for the time, giving it

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something like a definite shape, that it may be submitted to experiment and calculation; but they lead on by deduction and correction, to the discovery of new phenomena, and so cause an increase and advance of real physical truth, which unlike the hypothesis that led to it, becomes fundamental knowledge not subject to change.[7]

This beautiful description of the point and function of a heuristic model simultaneously reveals a characteristic facet of the thinking of many nineteenth century scientists: they were indeed convinced that they were stockpiling "real physical truth" and "knowledge not subject to change."

After the students learn something of the conceptual revolution associated with the elements of relativity, or after they have seen some of the failures of Newtonian and Maxwellian physics in the atomic realm, it is interesting to ask them to contrast with Faraday's statement the sadder and wiser one of J. Robert Oppenheimer:

> We come to our new problems full of old ideas and old words, not only the inevitable words of daily life, but those which experience has shown fruitful over the years. . . . We love the old words, the old imagery, and the old analogies, and we keep them for more and more unfamiliar and more and more unrecognizable things.[8]

In the light of such perspectives, students spontaneously begin to articulate some sense of why most scientists now view scientific knowledge as mutable and provisional rather than permanent and final. They anticipate limited ranges of validity to successful theories, and are fully prepared to find a deeper regression of unanswered questions behind every answered question.

In still another sequence involving models that transcend direct sense experience, one can get students to follow and examine the evidence that led to our belief in the atomic-molecular structure of matter as well as the structure of atoms themselves. They must be allowed to doubt with the early participants, to articulate uneasiness about the interpretation of some of the evidence—not just stuffed with a few disconnected and, in themselves, unconvincing arguments, followed by an assertion of the end results. The original doubters, after all, were a far from foolish company. Many illustrative gems line the way through such a sequence. Dalton, for example, in his original attempts to develop a quantitative atomic-molecular theory, confronted chemical data in the form of percentage composition by weight of various compounds. The only regularity that had been noted in these data was the so-called law of definite propor-

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tions—a fixed percentage composition of any definite chemical compound—and even this was still a matter of some controversy and uncertainty.

Dalton's preconceptions concerning the corpuscular constitution of matter led him to give particular consideration to cases in which a given pair of elements (say carbon and oxygen) form more than one compound, and it occurred to him that if 1.0 gram of carbon combines with 1.3 grams of oxygen in one compound, then for the same 1.0 gram of carbon in the other compound, one should find perhaps 2.6 or 0.65 or 3.9 grams of oxygen, or some other quantity that bore a small whole number ratio to 1.3. One would expect just such simple numerical relations if compounds did indeed consist of molecules made up of small numbers of atoms of the combining elements. The data had never been examined this way; this particular orderliness lay hidden behind the unrevealing percentage compositions. Dalton looked, and the order was there; he *predicted* what is now glibly known as the "law of multiple proportions." (In many modern courses, this law, if it is considered at all, is presented as though it had been known initially, and provided a priori evidence for the atomic theory.) The point here, of course, is that very frequently "facts" do *not* speak for themselves. In this instance, the facts had been available for a long time, but they were not even seen until looked for through the lenses of a theory; then suddenly their presence fed back as a dramatic confirmation of the theoretical conception that revealed them.

The story of the famous "Piltdown Man" hoax that was exposed in the 1950s is an inverse illustration of this idea. Many paleontologists accepted as genuine the fossil with the manlike skull and apelike jaw, because their theoretical preconceptions led them to expect an evolutionary sequence in which brain development led the way for changes in other parts of the body. They accepted the forgery for almost forty years, even though it was well known that it did not fit any reasonable niche in the humanoid fossil sequence. Here again, facts did not speak for themselves; they were viewed through the lenses of a theory, and the theory led many astray.

In a genuinely liberal (i.e., "liberating") educational enterprise, it is essential that the broad, general characteristics of any intellectual enterprise be brought to light, but this cannot be accomplished through vague generalizations disconnected from the visceral effort that goes with mastering the subject matter. To develop scientific literacy, it is

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essential to master at least *some* reasonable amount of subject matter in order to give meaning to the generalizations.

ILLUSTRATING CONNECTIONS TO INTELLECTUAL HISTORY

In properly paced introductory courses, there are many ways of making students aware of the role of science in their own intellectual history. For example, in working in the field of elementary school science instruction, I have more than once encountered the following sequence: A child asks why objects fall, and a teacher (or parent) responds, "Because of gravity." The impression is instilled in the child that a *reason* has been given that explains both cause *and* effect. There is no inkling on the part of either the giver or the recipient that the technical name conveys neither knowledge nor information and merely conceals ignorance. Few students, teachers, or citizens have any awareness of the history of this term—that "gravity" started as the designation of a teleological effect, a "drive" or "desire" on the part of the elements earth and water (and their mixtures) to seek the center of the earth; that Newton, explicitly eschewing knowledge of mechanism or process of interaction, made the grand surmise that, however mysteriously it might operate, the same effect that makes the apple fall binds the moon to the earth, the planets to the sun; that, despite the beauty and elegance of the general Theory of Relativity, to this day we have no idea of how gravity "works."

Very few students have any conception of the revolutionary thrust of seventeenth century science—the discarding of the notion that the heavens and heavenly bodies were made of a different substance and obeyed different natural laws from those of the terrestrial sphere; the subsumption of the entire universe under one system of humanly comprehensible natural law; the extension of the universe to infinity and the concomitant removal of the literal sheltering heaven from close overhead. Here was a profound turning point in our intellectual history; the personal outlook of every individual toward himself and toward his place in the universe is deeply conditioned by this heritage from Galileo, Newton, and other seventeenth century natural philosophers. An educated man should be aware of such a heritage in historical and intellectual terms, not in the mere assertion of end results. Beautiful presentations of this story are available at undergraduate levels,[9] but they are not widely used even in general education

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courses, and make virtually no appearance at all in curricula for scientists and engineers.

Yet, if these historical and intellectual aspects were brought out explicitly in introductory science courses, they would enormously enrich and enhance any study of the Enlightenment in courses in Western Civilization, and would stimulate a healthy diffusion of ideas through the membranes that now divide one course from another. Students are, for example, astonished to find how many aspects of the rhetoric used by the Founding Fathers in our historical documents are traceable through the Deists back to Locke and Newton.[10]

As an example of a connection to literature, consider these lines from "Morning Song of Senlin" by Conrad Aiken:[11]

> The earth revolves with me, yet makes no motion,
> The stars pale silently in a coral sky.
> In a whistling void I stand before my mirror,
> Unconcerned, and tie my tie.

Aiken simultaneously invokes the law of inertia, Galilean relativity, and the Newtonian cosmology, and embellishes all with a touch of irony and paradox. This is a clearly modern view; nothing like it could possibly have been written in the sixteenth century. On another plane, it is fascinating to compare these lines with Milton's equivocation between the Ptolemaic and Copernican systems in *Paradise Lost.*

Another profoundly influential sequence, emanating from technology, overarching and eventually unifying all the sciences, and having a pervasive impact in intellectual history, is the story of the "principles of impotence." Beginning in early times with a growing qualitative recognition that Nature conspires against our "getting something for nothing," against our achieving endless supplies of matter, motion, change, or warmth without effort and cost, the eighteenth century began to quantify a few of the relevant concepts. The "nothing can be created by divine power out of nothing" of Lucretius became, in the beautiful experiments of Lavoisier, the Law of Conservation of Mass. The concepts of mechanical energy began to emerge, but their connection to heat was not yet apparent.

The nineteenth century saw the grand synthesis of the First and Second Laws of Thermodynamics: the unification of mechanical energy and heat, and the conservation of energy over all; the possible and impossible directions of spontaneous change and the trend toward equilibrium; the possibility of converting a given amount of

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work entirely into heat contrasted with the impossibility of converting a given amount of heat entirely into work; and the subsumption of all changes in state—mechanical, chemical, thermal, electric, magnetic—under just those two laws. The quantified forms of the principles of impotence, emerging out of the technology of the Industrial Revolution, brought impressive and comprehensible order out of the chaos of disparate forms of change, profoundly directing and influencing the thought, for example, of social philosophers such as France's Georges Sorel[12] and historians such as Henry Adams.[13]

The nineteenth century had seen mass and energy as two separate, closed systems, each maintaining its own integrity of conservation. The twentieth century, through the conceptual revolution precipitated by Einstein, began to comprehend mass and energy as a unity rather than a dichotomy, and as interconvertible as work and heat. This led to the comprehension of how a radioactive material could maintain itself, apparently indefinitely, at a temperature higher than its surroundings; how the sun could keep shining for the enormous extent of geological time; and finally, how the prodigious energy confined in the atomic nucleus could be unleashed.

The sequence leads directly to all the moral, ethical, and societal problems that eventuate from the application of the resulting technology to peaceful industry, on the one hand, and to warfare, on the other. But the story and its influence on human society began long before Fermi and his associates constructed the first nuclear reactor in Chicago. I would hope to have students see some of this, with its ever-growing intensity, in the rich perspective of intellectual history, not just in a narrow view of the immediate scientific and societal end results.

VARIATIONS ON THEME

The preceding illustrations of epistemological, philosophical, and historical aspects of science, which, I submit, do infuse liberal and humanistic perspectives into any curriculum, happen to be personal favorites of mine. I present them for the purpose of being specific in my illustrations and not to advocate them above the host of other possibilities. Each teacher must select ones that appeal to him (or her) and that he (or she) can articulate to students in the most stimulating and compelling way. There is a whole array of aspects that James Conant referred to as the "tactics and strategy of science." There is the fascinating, partly scientific, partly sociological problem of vali-

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dation and acceptance of scientific theories. There are the philosophical problems of positivism and the questions concerning the "reality" of entities that transcend our senses: atoms, molecules, electrons.

There are also, of course, the pressing social problems that stem from the release of nuclear energy; the application of science to warfare; the possibility of synthesizing living matter and of controlling the genetic development of human beings; the problems of controlling and limiting abuse of our terrestrial environment. I have no intention of minimizing the significance of these vital problems, but I have reservations about launching into analyses or discussions of them prior to the point at which students understand the underlying scientific and technical subject matter. If they have engaged in the necessary prior study, or if the necessary background is conscientiously developed as the need arises, such discussions can be educationally fruitful and significant. If the problems are engaged *without* the requisite background and understanding, as is unfortunately sometimes done, the enterprise becomes specious, and students are misled into thinking that they have pursued deep inquiry whereas they have only dealt in vacuous generalizations, devoid of genuine thought and substance. This is *not* the path to literacy.

It is clearly not possible to do everything one would like to do along these lines. It is impossible to consider every important problem, open every significant perspective. The time is long past when we could teach our students all the things they must know. It is hardly an original assertion that the only viable and realistic function of higher education is to put students on their own intellectual feet: to give them conceptual starting points and an awareness of what it means to learn and understand something so they may then continue to read, study, and learn, as need and opportunity arise, without perpetual formal instruction.

The essential criterion is that students must not end up regurgitating secondhand pronouncements about the nature and processes of the scientific enterprise without ever having articulated any such insights out of their own intellectual experience. Without at least some participation in comprehension and interpretation of scientific concepts, theories, and philosophy, students learn no more from secondhand statements about science than they learn from a commentary on poetry without themselves having read the poetry, or a discussion on the philosophy of history if they lack the knowledge of the history of anything.

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Rather than plunging into levels of material utilizing concepts and relationships well beyond the students' present comprehension, if we were to allow them the opportunity to confront science through some of the more modest insights and experiences I have tried to illustrate above, I am convinced that they would develop lasting insights far more consonant with our often postulated objectives of liberal education. Such insights would contribute to the development of better-educated individuals and more intellectual citizens in exactly the same way as do an awareness of history and a sensibility to literature.

ASPECTS OF IMPLEMENTATION

Although I would encourage, particularly at upper division levels, occasional special courses devoted to specific important problems, using team-teaching—despite its relatively high cost—to assure interdisciplinary perspectives, I nevertheless believe that a great deal can be accomplished in the lower division level in existing curricular structures.

The walls separating courses in the sciences, the humanities, and the social sciences need to be made more permeable. In the illustrations I have given, I have tried to show how a science teacher might enhance the liberal content of his courses by becoming, through a deliberate effort, more literate and articulate about historical, philosophical, epistemological, or societal overtones in his particular field of science than he was prepared to be in his own education. Materials to this end are readily available both for teachers and students, and only a little ingenuity is required to devise questions, homework problems, and paper assignments that will lead students to confront ideas which transcend the sterile end results of particular modes of calculation or problem-solving.

It is true that, in our present science courses, infusion of such material would force us to back away from the already insane volume and pace of coverage that are imposed on our willing and uncritical students. It has for long been my contention that we are crushing our students into the flatness of equation-grinding automatons and forcing them into blind memorization of problem-solving procedures. We do not even give them a chance to begin to understand what understanding really means. Were we to require that they understand concepts and lines of reasoning within the perspectives I have outlined, we would be setting far higher intellectual standards and de-

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manding far higher performance than we now attain, with all our vaunted "coverage." This would *not* be a "watering down"; rather, it would be a "raising up." I know at first hand that students can and do respond to such demand. It is futile to exhort the students regarding the importance of liberal education and to give them nothing but ringing platitudes. We must be sufficiently knowledgeable and concerned to bring before them compelling and significant instances of intellectual, moral, or aesthetic experience. To this end, the instructor of science or engineering must exhibit his own capacity to deal with such dimensions, else the exhortation will be hypocritical. How can we demand that the students do something we will not do ourselves?

But the burden is not on the technical instructors alone. The walls must be made permeable in the other direction also. Instructors in the humanities must cease running from "hard science," as most of them probably did during their undergraduate careers; they most bring themselves to master at least a *few* of the "How do we know . . . ? Why do we believe . . . ?" questions I mentioned earlier, and they must treat scientific subject matter and its consequences knowledgeably in their own courses—for example, Newton's influence should be *seriously* discussed (*not* casually and superficially) in any history course dealing with the eighteenth century. The humanist and the social scientist must set an example for the students in the same way I demand of my technical and scientific colleagues. How can we expect the students to cease running from anything that makes them feel intellectually insecure if we persist in running ourselves?

I labor under no illusion that all this can be easily accomplished, but I see virtually no really effective alternatives if we are to achieve some fraction of our grandiose objectives. I did *not* receive this kind of education as an engineering undergraduate. If I have survived that education intellectually, I have done so by climbing out of the pit by my own hand-and-toe holds in the subsequent years, and I labor under all the wounds and severe limitations that constrain one in such circumstances. I have found the effort, however, highly rewarding.

THE PROBLEM OF COGNITIVE DEVELOPMENT

If we accept the premise that our liberal education objectives entail thinking, reasoning, and understanding on the part of the students, it is essential that we take into account the empirical results of current studies of cognitive development. Such studies,[14] usually based on

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administration of two or more of the now-classic Piagetian tasks, are showing, with remarkable reproducibility, that no more than about 25 percent of the cross-section of college students have developed the capacity for abstract logical reasoning at the level of these rudimentary tasks; further, that up to 50 percent of the students still use predominately concrete patterns of reasoning, while the remaining 25 percent are in transition, exhibiting only partial success in the formal reasoning tasks.

Students *do* have intellects capable of development beyond this point.[15] Such development, however, is necessarily based on practice and experience with important modes of reasoning, *repetitive* practice leading, in Piaget's terminology, to accommodation and equilibration. Most college students are very much in need of practice in the following modes, and practice must include the opportunity to detect and correct error:

1. Forming and understanding simple propositional statements and one-step or two-step syllogistic statements

2. Recognizing when they do not understand something they have read and identifying the point on which the lack of understanding hinges

3. Doing elementary hypothetic-deductive reasoning (i.e., visualizing in the abstract the possible consequence of various changes imposed on a system)

4. Recognizing the circumstances under which cause-and-effect relations can or cannot be established (i.e., having grasp of the logic of control of variables)

5. Doing elementary correlational reasoning

6. Doing arithmetical reasoning, utilizing ratio and division, including simple scaling of areas, volumes, or other commonly encountered variables

7. Translating symbols into words and words into symbols (as in the verbal interpretation of graphs or other visual presentations and the translation of verbal statements into graphs or arithmetical operations)

As I have already pointed out, the volume of material thrust on students in the majority of liberal education science courses, and the pace in which it is given, preclude the exercise of the time-consuming

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operations of thinking, reasoning, and understanding. The majority of students are thus forced into blind memorization, and they eventually come to see all "knowledge" and "understanding" as the juxtaposition of memorized names and phrases. They are not held to and tested on the reasoning; they are tested only on the memorizable end results. In these circumstances, there is essentially no hope of developing insights and understanding that characterize genuine scientific literacy—or, for that matter, literacy in any field requiring abstract logical reasoning.

If we really wish to succeed in our liberal education objectives, it is essential to start from the premise that the students *have* intellects capable of development and use. Then it is necessary to give them the opportunity to think, to reason, and to develop intellectually by providing material at a pace and level that make assimilation possible. Genuine understanding of a limited range of fundamental subject matter would testify to far higher intellectual standards and requirements than regurgitation of memorized jargon with respect to advanced or topical subjects.

THE PROBLEM OF TEACHER EDUCATION

It is not difficult to see that far and away the most leverage and the greatest potential for improving public understanding of the subject matter, methods, limitations, and social impact of science reside in the elementary and secondary schools. With genuine understanding of basic concepts at this level, subsequent levels of instruction would be enormously facilitated. Students might even come to college and university with levels of reasoning skill and subject matter background that would enable them to penetrate aspects of modern science that they now find hopelessly unintelligible. With such an improved background, even our mass-production system of lecturing to large classes might be considerably more effective than it now is.

Such progress is impeded at the present time, not by the lack of adequate curricular materials, but by the inadequacy of teacher education in the sciences. It is unlikely that any curricular materials, however high their potential for cultivating thinking, reasoning, learning, and understanding, will ever be "teacher-proof." A teacher can always negate the intent of the materials by attitude, invidious comment, and, most significantly, by what he or she chooses to test for. The real intellectual values of a course are established by tests rather than by texts. If improved curricular materials are to be suc-

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cessfully implemented, we must have teachers who are secure in the use of the materials. "Security" in this context means both thorough understanding of the subject matter's content and thorough understanding of the underlying pedagogical intent and design—which is impossible without the former understanding.

For example, intrinsic weakness of the materials is *not* the cause of the too-modest success in implementing the existing fine elementary school science curricula.[16] Rather, it is that college science preparation fails to provide elementary schoolteachers with the knowledge and understanding necessary for effective use and implementation. Our work with both pre-service and in-service elementary teachers at the University of Washington shows that the two groups are initially indistinguishable: the majority use concrete rather than formal patterns of reasoning; they cannot do arithmetical reasoning involving division (i.e., very few can do the word problems of fifth-grade and sixth-grade arithmetic); they do not control variables; they cannot visualize possible outcomes of changes imposed on a system; their "knowledge" of science resides exclusively in memorized names and technical terms, and because they lack adequate operational understanding of these names and terms, they are unable to reason with them in any specific instance.

In other words, our elementary schoolteachers, if they have had any physical science at all, have had courses of the variety criticized in an earlier section of this paper. Such courses do not help the future teacher exercise patterns of reasoning; they do not engender understanding of the subject matter. The future teacher is left with a half-remembered string of words such as nuclei, lasers, strange particles, angular momentum, and black holes; left, further, without any understanding of the concept of density, of floating and sinking, of the law of inertia, of the distinction between heat and temperature, of the origin of the phases of the moon or the annual motion of the sun, of the notion of electric current in the simplest resistive circuit, or of the most prevalent everyday phenomena of light or mechanical wave motion. The good elementary school science curricula wisely pursue the realms of everyday experience rather than esoteric vocabularies of modern physics, and the teachers find themselves at exactly the same level of initial knowledge as the children. I have heard honest and perceptive teachers volunteer this remark about their present condition in exactly these terms.

Time and again in our investigations, we have confirmed the empirical observation that adults (pre-service and in-service elementary

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teachers) acquire the abstract reasoning patterns and the conceptual understanding conveyed in the elementary science curricula only by overcoming exactly the same obstacles, hurdles, and difficulties that are experienced by the children—and at a no more rapid, and frequently slower, pace than they do. A major part of the effort expended in short workshops intended to help schoolteachers implement the new elementary curricula has been completely wasted because of the failure to recognize the necessary time element. Their college background has left the vast majority of these teachers at the same point as their pupils. It is illusory to hope that a brief indoctrination about the "philosophy of the program" and subsequent immersion in the materials will induce understanding of the content. We have found that only slow, patient traversal of both abstract reasoning patterns and subject matter will give the teacher the kind of security that leads to successful implementation.[17] In the meantime, unless and until we change our college courses and curricula, we will continue to produce elementary, intermediate, and secondary schoolteachers who are in need of remediation the instant they graduate. But this is not inevitable. Our investigations demonstrate that the large majority of pre-service and in-service teachers do develop the requisite competence given the proper opportunity.

A very common manifestation of the current inadequacy of the subject matter background of elementary schoolteachers is their reaction to the better curricular materials that are available for their use. In some instances, the materials simply stay locked up in closets, while the teachers, if they are obligated to teach science, proceed to lecture out of the standard older texts. In other instances, teachers, insecure in the face of the new materials, finding them "too difficult" for the children and unaware that the trouble lies in their own lack of understanding, band together and direct their energies and good intentions to writing materials of their own. The result is invariably trash that is full of errors, misconceptions, and misstatements, and that probably has negative educational value. (It must be reemphasized that the existing excellent elementary school materials referred to previously[18] were developed by mature and highly competent scientists who had the necessary perspectives and understanding.)

Research on teaching and learning may give us better instructional materials, but these materials will never have a really widespread impact in the schools unless we produce teachers who can implement them. This is a major problem, and it remains rooted at the college-university level. Accusations and recriminations made against ele-

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mentary and secondary schoolteachers are, for the most part, unwarranted and unjust: "The fault, dear Brutus, is not in our stars . . ."

Besides understanding of subject matter and exercise in the use of formal patterns of reasoning, one other aspect of teacher education that deserves attention is behavior in the classroom. The good, new science curricula are organized not around lecturing and inculcation by the teacher, but around exploration, trying and erring, and by talking and listening, arguing and explaining, among the students themselves. (There is evidence that when competently implemented, the science materials simultaneously enhance reading comprehension and arithmetical reasoning capacities in the children.[19]) In many instances, when children are following an erroneous course, it is important that a teacher direct their attention to inconsistencies or contradictions inherent in what they are doing and guide them to revision or correction without immediate assertion of a "right answer." Such behavior takes confidence, security, and command of content and reasoning on the part of the teacher; lecturing and asserting the right answer are much easier, and are the refuge of the insecure. But even with adequate subject matter background, it is asking too much to expect such sophisticated behavior of a young person thrown into a new classroom. The pre-service teacher needs both prior example and instruction. Many researchers in this country and abroad consistently show that teachers tend to teach as they have been taught. If we do nothing but lecture at our pre-service teachers, they will lecture in their own classrooms, regardless of the indoctrination they may be given (also by lecturing) in their "methods" courses in the departments of education.

It is essential that we set aside courses for future teachers that are taught in small classes in exactly the way we wish to have the elementary science curricula implemented. The science course then becomes a methods course as well, as it should be. With teacher education of this kind, we can begin to hope for a shift in the schools that will have a highly significant impact on the feedback to college level.

A ROLE FOR THE COMPUTER

One outcome of current research and observation over a wide range of different courses, made repeatedly in our group at the University of Washington, is that many students do not break through to command of a particular concept or sequence of reasoning unless they can be reached in a one-on-one dialogue.[20] This is particularly

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true of pre-service and in-service elementary and secondary teachers. Specific examples are: arithmetical reasoning using division; distinction between velocity and acceleration; interpreting position-time and velocity-time graphs in words and in motions executed by one's own hand; distinction between heat and temperature; forming and using the model for origin of phases of the moon (i.e., dealing successfully with questions such as "Would you expect to see a full moon rising at midnight? Why or why not?"); forming and using the model of current and concept of resistance to predict brightness changes that would result from alterations (shorts, removal or insertion of other bulbs) imposed on simple circuits composed of batteries and flashlight bulbs.

Such one-on-one dialogue with a single student can easily take as long as twenty to thirty minutes or more. It is barely possible to do this in small classes, and is out of the question in large ones. One might adopt the view that students who cannot master such simple and basic concepts or reasoning modes do not deserve additional effort on the part of the staff and do not belong in science courses. Enlightened self-interest, however, if not a broader objective, dictates a less callous view. Among the students who fail or who simply disappear from our courses (or who never enroll in the first place because of their deep fear and insecurity), and who could be saved by one-on-one help at strategic points, are many potentially promising minority students as well as most of our future elementary schoolteachers, not to speak of many others.

Here is a point at which modern technology can be of some assistance. The coming-of-age of the stand-alone microcomputers with graphic capability offers the prospect of making one-on-one instructional dialogue[21] practicable in spite of numbers. The problem becomes one of writing effective dialogues that pull students over the early, most severe obstacles, and help put them on the way toward further learning, with decreasing dependence on such assistance.

The writing of effective dialogues will of necessity lean heavily on the results of researches in cognitive development. Not only must a skillful author have a broad awareness of what is being learned in general about cognitive development and patterns of logical reasoning, but he must also draw heavily on the detailed, concept-by-concept student protocols. We ourselves very rarely make correct conjectures about the students' preconceptions, misconceptions, and linguistic difficulties. Yet, for a really good computer dialogue, the most important and most difficult provisions an author must make

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are the ones that lead a student to rectify *incorrect* responses; it is easy to take care of the correct ones. The exercise of writing computer dialogues has an additional and valuable secondary effect on the authors themselves. Time and again, after the intensive intellectual exercise of outlining such dialogues in a workshop, I have seen veteran teachers lean back with a traumatized air and say, in effect, "I will certainly never teach *this* subject matter the same way again. I cannot see how I ever accepted the presentation I have been using. It is full of holes that must have confused the students."

LEARNING FROM PAST EXPERIENCE

With the present resurgence of concern about education of scientists and engineers and about public understanding of science and technology, some individuals are pointing to what they regard as the "failure" of the curriculum development efforts of the fifties and sixties, and are advocating a new round of preparation of text materials, hoping that *this* time the materials will be "better" and "more effective." It seems to me that this is a fallacious and forlorn hope. Although many of the existing curricular materials can certainly be improved in pedagogical quality, this alone will not overcome the real obstacles and underlying problems. Curricular materials, however skillful and imaginative, cannot "teach themselves."

I do not consider the science curriculum writing of the fifties and sixties to have been a failure. At the time these efforts were undertaken, principally under the stimulus provided by the National Science Foundation, new text materials, particularly ones rooted in laboratory and observational experience, were very badly needed. Existing texts were obsolete, full of errors and misstatements, and intellectually sterile. They had been copied and recopied for several generations by authors who themselves did not have adequate and up-to-date knowledge of the subject matter.

In the heady, evangelistic atmosphere of two decades ago, leaders in the various scientific and technical fields brought imaginative insight, current perspectives, and correct logical underpinnings to the new materials. It is true that the materials produced were not uniformly high in instructional quality. Some of these materials were too rapidly paced for the age groups for which they were intended. Some started by asserting end results of sophisticated developments in other scientific fields, required the students to memorize these end results without examination of any underlying "How do we know . . . ?

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Why do we believe . . . ?" questions, and proceeded to drown the students in incomprehensible consequences of the initial, unsupported assertions. Some of the curriculum developers, not having the benefit of more recent insights into the actual levels of capacity of different age groups for abstract logical reasoning,[22] went off into abstractions completely beyond the grasp of the pupils they were ostensibly addressing (and of many teachers as well). Mathematics, in particular, suffered from such misdirection.

However, despite some of the misplaced effort, a significant number of excellent curricula were developed. In my opinion, the best ones are among those designed for elementary school.[23] In these materials, children start from scratch, with no presupposition concerning prior "knowledge" of technical terms. Ideas come first and names afterward. Concepts are synthesized out of observational experience rather than received through didactic presentation. Reasoning starts at concrete levels and, provided it is under the guidance of a competent teacher, gradually proceeds toward the abstract. Repeated intellectual experiences of this kind stimulate the emergence of abstract reasoning capacity and enhance its subsequent development. Some sound and potentially effective materials were also developed for junior high-school and high-school levels. In most instances, these materials are mismatched to the particular age level the developers had in mind, but they are usually well suited to students one, two, or three years older.

My point is that a substantial body of interesting, imaginative, and educationally sound material *was* developed, despite some mistakes. These materials are not obsolete or out of date. Their adoption and implementation has indeed been disappointing, but I contend that the "failure" which is adduced in this connection does not stem from deficiencies in the quality or character of the materials themselves. The failure stems rather from external causes. Although the better of the existing curricula are surely not the last word in educational sophistication, and although improvements are certainly possible in the light of improving insights into aspects of cognitive development, I am convinced that a new generation of materials would suffer exactly the same failure in adoption and implementation from the same extrinsic causes.

There were two principal causes for failure. One was inadequacy of logistic support, particularly in elementary and junior high school, for teachers venturesome enough to try the new curricula. Hands-on, laboratory-oriented materials require continual maintenance and re-

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supply. Busy and overloaded teachers need sustained support in using such materials; they cannot take care of the logistics in addition to all the other duties they are expected to discharge. Although they might make the extra effort in the initial wave of enthusiasm (and many of them did), such effort is impossible to sustain over long periods of time. The necessary logistic support was rarely strong, even at the beginning of adoptions, and it rapidly melted away altogether in the seventies, with growing financial pressures on the schools.

Thus, one formidable obstacle that must be overcome at all levels in the schools is that of logistic support. It is illusory to suppose that widespread scientific literacy will ever be successfully cultivated through instructional materials based on purely verbal inculcation. The necessary understanding, reasoning, and mastery of concepts and ideas will evolve, in the great majority of ordinary individuals, *only* from concrete observational experience. It is true that some gifted individuals do break through to scientific understanding, and to abstract reasoning in general, without such concrete help. But this small fraction of the population has always broken through, perhaps with some delay, regardless of the circumstances. We are indeed fortunate that this is the case, for otherwise scientific literacy would be far lower than it actually is. Our reiterated goal, however, is a large increase in the literate fraction. This goal will not be attained without providing the majority of young students with hands-on experience and with sustained guidance in carrying reasoning from the concrete to the abstract.

The second, and most significant, cause of failure in adoption and implementation of the better curricular materials lies in what happened in the retraining of teachers. Huge amounts of money and effort were poured into summer institutes and academic year programs, most of them under the direction of college and university faculty members. A few of these programs were beneficial because the staff recognized that the teachers had developed little genuine understanding of scientific subject matter in their previous school and college courses and were very nearly at the same level of conceptual development as their pupils. Accordingly, it was realized that the teachers must be guided slowly and carefully through the intellectual experiences they were subsequently to convey in their own classrooms. In the majority of teacher training programs, however, this necessity was not understood or appreciated. It was falsely assumed that the teachers, elementary through high-school level, really under-

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stood the very elementary science they were to be teaching (or that they would quickly learn it, along with the students, from the marvelously lucid new materials). In the summer institutes and other programs, the teachers were thus given lectures about the "educational philosophy" of the materials, the substance of which they still did not comprehend. Or, they were given more advanced subject matter, also totally incomprehensible, in order to extend their perspectives and knowledge of most recent progress in the field. Or, in the largest number of cases, they were simply given more of the same rapidly paced, irrelevant, and unintelligible college courses that had had no visible intellectual effect in the past. In such instances, the teachers were no better able to handle the new curricular materials than they were before coming to the training program. It was not their fault that they had no awareness of this deficiency and that in subsequent, disappointing classroom experiences with the new materials, they ascribed the trouble to the difficulty of the materials rather than to their own inadequate understanding. (Let me hasten to say that I am not tarring *all* teachers with this brush. I know personally, and I continually hear about, superlatively competent teachers at every level. These are far too small a fraction, however, to make for solution of the problem.)

If we wish to produce widespread improvement in public understanding of science, we will have to take significant steps toward mitigating the two principal causes of our previous failure. The problems are very difficult, but they are not intrinsically insoluble; the remedies are necessarily fairly costly, and by far the most difficult part of the problem is conveying comprehension of it to our college and university faculties. If they do the same thing over again in teacher training, there will be no progress.

Curricular materials, however fine, will never achieve our goals entirely by themselves. They may improve things for the especially gifted, but they will not solve the problem for the vast and perfectly respectable majority. Unless the essential underpinnings I have pointed out are provided, tinkering with new curricular materials will again absorb huge amounts of money and effort, and will leave us exactly where we are at the present time. We will have a new crop of complaints about failure and inadequacy of the materials and a revived demand for another wave of needless curricular development. Attainment of wider scientific literacy will keep receding into the infinite educational perspective.

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ENDNOTES

[1]I wish to make it clear that I am not deprecating student opinion as such. I question the specious use of such opinion by faculty who have failed to provide the students with an adequate frame of reference.

[2]See, for example, the text materials themselves and the descriptions of goals and objectives accompanying elementary science curricula such as *Elementary Science Study* (ESS) (New York: McGraw-Hill, Webster Division) and *Science Curriculum Improvement Study* (SCIS) (Nashua, New Hampshire: Delta Education).

[3]A.B. Arons, "Some Thoughts on Reasoning Capacities Implicitly Expected of College Students," in *Cognitive Process Instruction,* edited by J. Lockhead and J. Clement (Philadelphia: Franklin Institute Press, 1979); A.B. Arons, "Cultivating the Capacity for Formal Reasoning," *American Journal of Physics* 44(9) (1976): 834; A.B. Arons, "Anatomy of an Introductory Course in Physical Science," Journal of College Science Teaching 1(4) (1972): 30; and A.E. Lawson, "Relationships among Level of Intellectual Development, Cognitive Style, and Grades in a College Biology Course," *Science Education* 64(1) (1980): 95.

[4]A.E. Lawson, "The Reality of General Cognitive Operations," *Science Education* 66(2) (1982): 229.

[5]Arons, "Some Thoughts on Reasoning Capacities." See also E.L. Chiappetta, "A Review of Piagetian Studies Relevant to Science Instruction at the Secondary and College Level," *Science Education* 60(2) (1976): 253.

[6]Unfortunately, this is *not* true of many other aspects of intellectual development, particularly the capacity for abstract logical reasoning. But this is another story, and as Mortimer Snerd used to say, a long and dirty one. See Arons, "Some Thoughts on Reasoning Capacities" and Chiappetta, "A Review of Piagetian Studies."

[7]Michael Faraday, *Experimental Researches in Electricity,* vol. 3 (New York: Dover Publications, 1965), P. 408.

[8]J. Robert Oppenheimer, "Communication and Comprehension of Scientific Knowledge," *Science* 142(3596) (November 29, 1963): 1144.

[9]Gerald Holton, *Introduction to Concepts and Theories in Physical Science,* 2d ed., rev. S.G. Brush (Reading, Massachusetts: Addison-Wesley, 1973). See also F.J. Rutherford, Gerald Holton, and F.G. Watson, *The Project Physics Course,* 3d ed. (New York: Holt, Rinehart, and Winston, 1981).

[10]A.B. Arons, "Newton and the American Political Tradition," *American Journal of Physics* 43(3) (1975).

[11]Conrad Aiken, *Collected Poems* (New York: Oxford University Press, 1953).

[12]R.D. Humphrey, *Georges Sorel, Prophet without Honor* (Cambridge: Harvard University Press, 1951).

[13]Henry Adams, *The Education of Henry Adams* (Boston: Houghton Mifflin, many editions).

[14]Arons, "Some Thoughts on Reasoning Capacities"; Lawson, "The Reality of General Cognitive Functions" and "Relationships among Level of Intellectual Development"; and Chiappetta, "A Review of Piagetian Studies."

[15]Arons, "Anatomy of an Introductory Course in Physical Science" and "Cultivating the Capacity for Formal Reasoning"; and Lawson, "Relationships among Levels of Intellectual Development." See also the series of papers on teacher education by L.C. McDermott in the *American Journal of Physics* 42 (1974): 668, 737; 44 (1976): 434; and *The Physics Teacher* 13 (1975): 523.

[16]See references cited in note 2.

[17]A.B. Arons, *The Various Language—An Inquiry Approach to the Physical Sciences* (and accompanying *Teacher's Handbook*) (New York: Oxford University

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Press, 1977). See also Arons, "Anatomy of an Introductory Course in Physical Science" and "Cultivating the Capacity for Formal Reasoning"; and McDermott references in note 15.

[18]See references cited in note 2.

[19]J.W. Renner et al. "An Evaluation of the Science Curriculum Improvement Study," *School Science and Mathematics* 73(4) (1973): 291. See also M.C. Weber and J.W. Renner, "How Effective Is the SCIS Science Program?" *School Science and Mathematics* 72(8) (1972): 729.

[20]A.B. Arons, "Thinking, Reasoning, and Understanding in Introductory Physics Courses," *The Physics Teacher* 19 (1981): 166, and Arons, "Cultivating the Capacity for Formal Reasoning."

[21]A.M. Bork, "Interactive Learning," *American Journal of Physics* 47(1) (1979): 5.

[22]Chiappetta, "A Review of Piagetian Studies."

[23]See references cited in note 2.

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Mary Budd Rowe

Science Education: A Framework for Decision-Makers

DURING PERIODS OF PERCEIVED CRISIS, national debate in this country inevitably focuses on the purposes and content of science education, on how it is conducted, and who has access to it. We are now entering such a debate, if in fact it has not already started. Part of the debate centers around what levels of government should be involved and in what ways; in other words, given that an acceptable set of recommendations will eventually emerge, who will pay for the effort to revitalize science education? Legislators, school board members, textbook and test writers and their publishers, school administrators, technical experts such as scientists and engineers, and curriculum supervisors—all are influential in setting science and mathematics education policies. What they need is a frame of reference within which to evaluate recommendations, plans, and policies. In this paper, I propose such a frame of reference. I use it to evaluate some of the current controversies concerning what ought to be done to improve the quality and appropriateness of science instruction, and conclude with some recommendations for action.

According to the proposed paradigm, a full science program consists of four interdependent parts: Ways of Knowing, Actions/Applications, Consequences, and Values (Figure 1). Using these components, we can examine science curricula, texts, instruction in classrooms, and even standardized tests to see whether all four are present. When we do, we usually discover that three of the four—implications for *action,* prediction of *consequences,* and the analysis of *value*—are either missing entirely or minimally treated at the elementary or secondary level. Yet these components are precisely what

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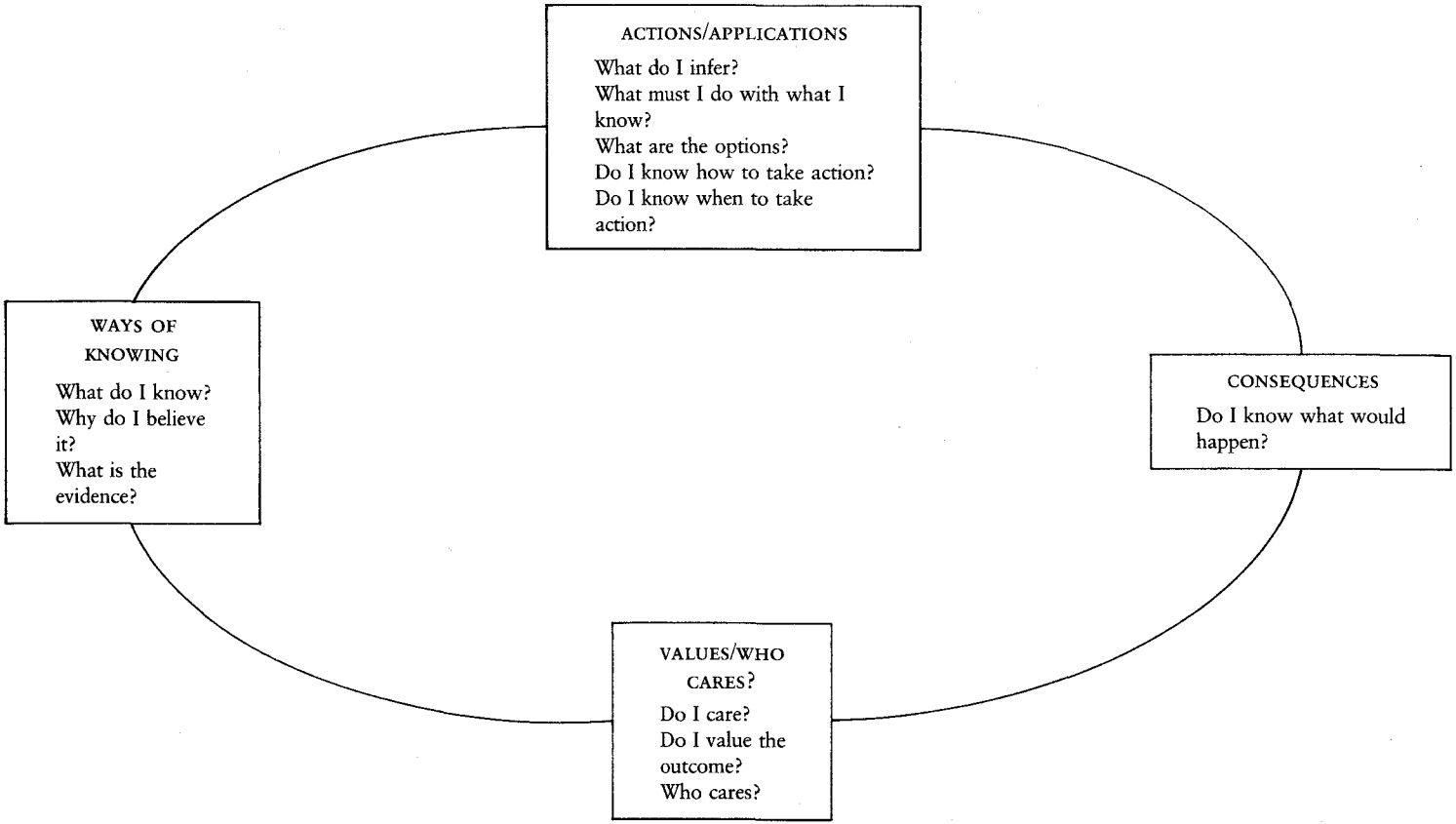
ACTIONS/APPLICATIONS
What do I infer?
What must I do with what I know?
What are the options?
Do I know how to take action?
Do I know when to take action?
WAYS OF KNOWING
What do I know?
Why do I believe it?
What is the evidence?
CONSEQUENCES
Do I know what would happen?
VALUES/WHO CARES?
Do I care?
Do I value the outcome?
Who cares?

Figure 1. Four Components of a Full Science Program

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are of greatest interest to the majority of students. Even then, only a portion of the questions under the heading "Ways of Knowing" receives substantial attention in texts, tests, or instruction, with most consideration given to what we are *supposed* to know and very little to why we believe or doubt it, as the case may be.[1]

Research on the learning and teaching of science, mathematics, and technological subjects suggests what we should do, but sadly, the current practice in teaching and textbook presentations fails to exploit this knowledge. If the research were applied in texts and instruction, both interest and achievement in science and mathematics would improve substantially, and at a relatively low cost (a subject I shall return to later).

None of the science programs in the past adequately exploited the need of students, particularly young adolescents, for answers to questions that they regard as important, what students call the "so what" of it all—actions, consequences, and values. Late in preadolescence and during the years that follow, youth in every country begin to develop a world view, a set of attitudes—a nexus of beliefs if you will—that ultimately affects their behavior. By observation, through experience, and by talking seriously with anyone who will converse with them, they form their own answers to a recurrent set of twelve questions.

1. What kind of country is this?
2. What values control activities?
3. Where do I fit in?
4. Do they expect me to succeed or fail?
5. How much effort do I need to make?
6. Is success worth the effort?
7. Can I get help?
8. Do I have the energy and endurance?
9. What happens if I do not make the effort?
10. What am I up against? What is the competition?
11. What difference can I make?
12. Do I care? Does anybody care?[2]

Ultimately, we have to decide what science programs, and other subjects as well, ought to contribute to their search for answers.

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Under Project Synthesis, a team of twenty-three science educators examined elementary and high-school programs to see how well they satisfied four major purposes of science education: (1) science for personal needs; (2) science suitable for dealing with social issues; (3) academic preparation for further study of science; and (4) orientation to careers in science and technology. Their aim was "to examine the countenance of science education as it exists at the precollege level and to make basic recommendations regarding future activities in science education."[3] Although they found no programs that satisfied all four goals in the four large databases and the most commonly used textbooks that they studied, they did find pieces scattered among the programs that could be fit together to fill out portions of the missing components in the science cycle described in Figure 1.

GAPS IN THE SCIENCE CYCLE: WHY THEY EXIST

Controversies about what the focus in science programs should be arise in part from the failure to keep all four components in perspective. Within the "Ways of Knowing" component, for example, we find the first major difference between what the scientists who led science curriculum reforms that began in the sixties thought was important and what was then, and continues to be, the predominant emphasis in schools. For the most part, teachers and texts concentrate on the question "What do I know?" Emphasis on this question tends to limit the teacher's function to one of conveying information and correcting student recitations. Knowledge is seen as a fixed commodity to be stored up for future use. ("Learn it now. You will need it next year.")

Ordinarily, science programs that operate under this conception of knowledge provide relatively little formal opportunity for students to discuss their own interpretations. The students' primary responsibility is to learn the official story well enough to be able to write it or recite it correctly, regardless of whether they understand it or believe it. Thus the coverage of large amounts of content becomes a prime objective.

Textbook publishers and testing services have responded to this objective overwhelmingly. Science books have grown by accretion, packed with more concepts per page, more pages per book, and more topics to be "covered" than ever before. High-school science

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texts average between seven and ten new concepts, terms, or symbols per page. Typically, the 300 to 350 pages assigned during a school year means that students are expected to learn between 2,400 and 3,000 terms and symbols per science course.[4] Thus, in a school year of 180 days, and in class periods of approximately fifty-five minutes each, twenty concepts would have to be covered per period, an average of one every two minutes. That there is very little discussion or inquiry should come as no surprise—there is no time for it.

Some sense of the frustration both teachers and students sometimes experience in the face of such pressure is epitomized by the remark of an exasperated ninth-grader as he slammed his very thick Earth Science text down on his desk—"Do you know what this is? It's a damn'd dictionary!"

Standardized tests, or at least teachers' images of them, reinforce the "coverage" pressures that teachers feel, and have as well some undesirable effects on students. Science instruction often amounts to no more than long lists of words to be looked up so that the definitions can be repeated in recitation and on tests. Implicit in this method of teaching is the notion that students are uncritical, essentially bottomless receptacles for information. When it comes to learning science and mathematics, at least, this is an erroneous conception. One has to wonder, parenthetically, what such learning contributes to the search for answers to the students' questions described above.

What students *do* learn is that someplace there are people who produce the "right" answers. There is always an official response to be recited whether or not one understands it or believes it. Recent research (to be described later in this paper) illustrates how deeply self-defeating this whole approach to science instruction is.

In the sixties, scientists who took part in the reform of science programs wanted more attention given to the other questions in the "Ways of Knowing" component—"Why do I believe it? What is the evidence?" They argued that to understand why science has become so important to the well-being of people and the prosperity of a nation, one has to look at its methods as well as its content. The methods create a capacity for progress by making possible a systematic increase of trustworthy knowledge—that is, knowledge that has been subject to test and verification. Thus they wanted to direct more attention to the methods by which researchers construct reliable knowledge. They wanted students to consider the roots of belief, to examine evidence, to construct explanatory systems of their own that

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were fundamentally "scientific" in nature. They encouraged students to seek alternative interpretations and to appreciate the provisional nature of explanations. Science, they believed, is a method of constructing reality that depends essentially on *action*. Through action, the correspondence between explanation and phenomena can be checked, and knowledge put to work on our own behalf. But the form of instruction they thought appropriate to achieve their purpose relied heavily on guided inquiry and extensive student discussion—students as active inquirers in search of explanations, as opposed to receivers of information *per se*—and this created serious problems for many teachers and students alike.

Only engineers had a full grasp of the implications of the "Action" component of the science cycle, but their influence on curriculum was limited. The engineering sciences provide a means for joining together the four components of the science cycle because they draw attention to the applications side, the "so what" of it all. Three categories of knowledge are important to the design of solutions to technical problems: (1) how things work (description); (2) why they probably work that way (explanation); and (3) what must be done to make desirable outcomes more likely and undesirable effects less likely (forecasting and control). Thus the "Actions," "Consequences," and "Values" components of the science cycle could be realized through the inclusion of an engineering perspective in both mathematics and science.[5]

Many of the scientists and mathematicians who took part in the curriculum reforms of the sixties felt that if the basic science in all the items under "Ways of Knowing" was strong, anybody could make applications. That expectation proved to be incorrect. Recent research in physics[6] and in mathematics[7] education suggests that strategies for making use of knowledge are complex and must be taught. Even students with good grades in physics and mathematics had great trouble putting their knowledge to use when confronted directly with phenomena, so-called real situations. Moreover, by failing to include sufficient emphasis on implications for action, texts and teachers alike eviscerate one of the most important sources of motivation to learn. Many students see little point to what they are being asked to learn, and have little enthusiasm for science in the way it is generally conveyed—namely, books that read like dictionaries and classroom sessions that require little interpretation and application from the students.[8]

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TRADE-OFFS BETWEEN GIVING INFORMATION AND ENCOURAGING INQUIRY

Inquiry-oriented instruction brings into contention the purposes of the program and the beliefs of the students about what is true and important. Moreover, it threatens the traditional role of the teachers in controlling the flow of content and determining what the final products of discussion should be.

Typically, teachers ask questions and students answer them. In the inquiry mode, however, more responsibility for producing and evaluating explanations and for asking questions shifts to the students. Attention moves from questions of what we know to how we explain what we know or believe, and in a fully implemented cycle, to discussion of the other three components that relate to application.

The inquiry process incorrectly conceived can lapse into an inquisition as easily as the "tell, text, test" procedure can. During a lesson on earth science, for example, a student's answer to the question why crystals formed in rocks immediately provoked another one from the teacher: "And why is that?" The student gave more information, and again the teacher asked, "And why is that?" After the fourth "why" from the teacher, the student answered in exasperation, "I don't know. God made it that way, and that is that!" Students may learn to say what they are expected to say but believe something else, and it is beliefs that ultimately guide action.

Instead of acting primarily as givers of information and inquisitors, teachers in the inquiry mode will function more as consultants to the student investigators and as managers of materials needed in the laboratory. The students' task will be to construct defensible explanations.

Students come to class with a host of what might be called homegrown conceptions of how the world works, conceptions that are convincing to them but that often turn out to be incorrect in terms of modern science. These misconceptions are quite resistant to change and frequently become barriers to further learning. We now know that simply telling them a different way of thinking fails to unsettle these deep beliefs. There is a growing body of research on specific misconceptions that appear to be learned relatively early in life. Physics ideas have been particularly difficult for people to acquire and use because of prior misconceptions.[9] One thing seems clear from this line of research: students will not exchange their naive explanatory systems for scientific ones by being told what to think and say about

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the two to three thousand concepts and symbols that are now treated in many classrooms and textbooks. The research seems to show that only through exposure to many counterexamples, plus a good deal of discussion and argument joined to experimentation, are they likely to transform their perspectives.

Wait-Time and Pacing Factors

Whatever variation of inquiry one chooses, and wherever in the cycle the class is, discussion and argument are essential to intellectual growth in the discipline and to the nurture of the embryonic roots of scientific wisdom. In fact, however, the prevailing pace of verbal exchange between teachers and students in science classrooms is much too fast for the necessary depth of thinking to take place. The speed of exchange that characterized recitations in the "tell, text, test" pattern proved to be much too rapid for the complex mental processing that the inquiry method requires to function properly.

When teachers ask questions, they generally allow an average of only *one second* for students to begin answers. After a student responds, teachers typically begin a reaction in slightly less than a second (an average of 0.9 seconds). While that rapid pace may be suitable for drill, it spells doom to the kind of discourse needed for more complex thinking. The effect of lengthening the pause following a question and after a response alters the quality of student thinking rather dramatically. *The changes that result,* only a few of which will be mentioned here, *highlight the connection between instructional strategies and the kind of thinking that students exhibit.* For example, the length of their explanations in one study increased on average from twelve to forty words, a 300 percent growth in science-related language production. Inferences were more likely to be linked to evidence without need for teachers to probe for the connections. Students asked more questions, something they rarely do under normal rates of pacing. Logical consistency of their explanations improved, and the number of suitable alternative ideas they expressed increased markedly. Essentially the same effects were found for secondary and elementary schools and in college science classrooms as well.[10]

Feedback

In the "tell, text, test" pattern, teachers focus on the correctness of student responses, signaled by reactions such as "Good," "O.K.," "Fine," "Right," "No, think again," and these are consistent with

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the emphasis on the question "What do I know?" Answers, for the most part, are either right or wrong.

Because feedback in inquiry-centered instruction is meant to improve the quality of student explanations, the teacher's task becomes considerably more complex. This kind of instruction requires deeper understanding of the subject and of likely student misconceptions. Feedback is meant to help students assemble explanations that meet such criteria as consistency, congruence with the data, and so on. Challenges to student explanations have three purposes: to resolve differences in explanations; to illustrate why controversy is essential to the progress of science; and to confront values that are implicit in the process of moving around the science cycle. To be effective in the inquiry mode, teachers have to make judgments continuously about the adequacy of student explanations in order to select activities or pose questions that will allow students to discover for themselves when their ideas need to be revised.

As discussed above, wait-times that are too brief have a negative effect on the quality of student reasoning in science. So, also, do too many verbal rewards ("Fine," "O.K.," etc.). Contrary to prevalent belief, a high rate of verbal rewarding has a depressive effect on the quality of explanations in science.[11] If an objective is to build student confidence in their ability to develop explanations and to resolve conflicts between prior conceptions and new explanatory systems, three instructional practices will help:

1. Overt verbal rewards need to be substantially reduced in order to create a relatively risk-free condition for testing ideas.

2. Average wait-times after a teacher asks a question and after a student responds need to be increased from the prevailing one second to three seconds.[12]

3. Students need many examples and a great deal of time to discuss them if they are to understand concepts well enough to put them to use.[13]

In short, the research seems to imply that the current emphasis on rapid presentation of many ideas, with too little time for discussion and too few examples, may produce students who are test-wise and knowledge-poor. The implementation of an inquiry approach, however, poses dilemmas for students as well as teachers at least some of the time. Three anecdotes illustrate how deeply embedded is the idea that there is only one official explanation.

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In a chemistry classroom in Palo Alto, California, *CHEM Study* (one of the inquiry programs developed in the late sixties), students answered questions as briefly as possible, and when the teacher pressed for alternative interpretations, they sat silent. Finally, one of them called out plaintively, "Why don't you just tell us the answer and get it over with? We have to take college entrance exams and need to know the right answers." Then he added, "This inquiry stuff is sometimes kind of interesting, but we haven't got time for it, and besides, it always ends up the same way—what we are supposed to think. We need to know the right answers."

The second illustration of the fact that young adolescents, wherever they may be, form their own answers to the basic questions described earlier comes from a sixth-grade classroom of boys in Kenya, East Africa, where another inquiry-based science program, the "African Primary Science Program," was taught. The sixty boys were organized in working groups of seven or eight each to conduct a small investigation using a few common chemicals. I was the consultant for one of the groups. The boys rather quickly got the idea of controlling variables, in this case, mixtures of chemicals, so that they could identify an unknown powder. Within the group there were differences of opinion about why some of the mixtures bubbled and others changed color. The questions and explanations were theirs, not mine. At the end of an hour, the teacher called the groups together to question them about their findings and explanations. To my surprise, the boys in my group gave answers that were at odds with those on which they had previously reached a consensus. Afterwards I asked them why they had done that. In Kenya, where the future of students depends heavily on their test performance, the response made practical sense, "Please understand, madam. We know the way of his knowing must be the way of our knowing, whether we believe it or not."

On a flight to Europe, an eleven-year-old boy from Baltimore watched me analyze some research data with the help of a calculator. At some point he startled me by saying, "How will you know if you are right?" Had he somehow read my own concern? "Where are you going to look it up when you get finished?" he wanted to know. Still begrudging the intrusion, I answered, "There is no place to look it up. I just have to use this answer until there is a reason to change it, maybe when other people think there might be a reason." He was not satisfied. "Someone has to know. If you don't have a book to look up the answers, then you have to ask the teacher." He paused,

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and then in a tone of sympathy said, "Sometimes they won't tell you. Won't your teacher tell you?" Certainly he had formed his answers to a few of the twelve questions listed earlier.

In science and engineering programs that stress inquiry, the balance between teacher control and student control of what happens in the dialogue is critical. How far off the track should teachers let students wander before redirecting them when they fail to recognize and remedy deficiencies? This question, asked repeatedly by puzzled, time-driven teachers, was echoed in a related form by certain of their students who never lost track of what was really important for their future: "What are they fishing for?"

Logistics

Conditions for operating satisfactory laboratory portions of science programs are much less favorable than they once were. The impact of the changes is greater on an inquiry mode of instruction than on the "tell, text, test" instructional pattern. Inquiry programs rely heavily on activities meant to arouse student curiosity and prompt spontaneous exploration of ideas. Today's classes are larger and more unruly. That means more materials need to be available and managed safely at one time. These conditions increase the risk of injury in an era when teachers are more and more vulnerable to suit.

Everything connected with operating a science program seems to be surrounded with more red tape and restrictions than was once the case—repairs and the purchase of new equipment and other materials involve more paperwork, permission for field trips is more difficult to obtain, safety precautions are more stringent, and so on. One hears remarks like the following from teachers who once ran first-rate inquiry-based programs: "Nobody wants to cooperate on anything anymore. The students don't want to do the work to prepare for field trips and the administrators don't really want you to go. It costs money, and they worry about the things that could happen." "I wait until the summer to take students on trips, because then I just get the ones who are interested. The others have ruined so much for everyone. They couldn't care less." "Because of insurance on the buses, we can't take trips beyond twenty-five miles from the school, and the museums are fifteen miles beyond the limit."

For many science teachers, the groups of bright, enthusiastic students who came to the laboratory after school to work on science projects of their own choosing were the greatest source of satisfaction. Here, inquiry went forward in a very natural way in what

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amounted to small research communities. With the disappearance of neighborhood schools, and the need to move large groups of students on tight bus schedules, afterschool programs, which gave science-motivated students the opportunity to work on projects and to spend time with others interested in science, virtually disappeared. Many schools still maintain an "activities" bus that takes students in the major sports and band programs home at the end of an extended day, but as one teacher remarked angrily, "They don't have room for the science kids. Football and band get priority."

Many teachers are reacting to the deteriorating conditions by retreating to what appears to be the safest and most energy-conserving version of the "tell, text, and test" instructional pattern. Laboratory equipment stands idle, and administrators wonder whether it was a bad investment. This, in turn, makes science, with its horrendous vocabulary and what many students consider to be irrelevant content, less attractive. It is treated increasingly as a second-language learning program.[14] Enrollments in nonrequired science courses are not rising,[15] and if we can believe the reports on science performance published by the National Assessment of Educational Progress, students know less science than they did a decade ago.[16]

SCIENCE AND FATE CONTROL

How well a nation thrives and how rapidly adaptation takes place depend in part on the extent to which a substantial portion of its people understand the connections between possession of scientific and technological knowledge and the power to act effectively on the world. The products of science and engineering indeed produce fundamental shifts in economics and world view, but the methods of science and the values attached to it have the power to shape our sense of purpose and to turn us into architects of our destinies. Too often, however, the way in which science is taught fails to convey any insight into its most powerful features.

As an enterprise, science transcends national borders. Education about science, however, takes place within ideological milieus. Some are hospitable to the culturing of scientific and technological sophistication; others stifle its development. The vigor of science and technology in a country depends in part on which of the two forms of *fate-control* orientation predominate in the culture. Fate control refers to a pattern of beliefs about the nature of the world we live in,

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one's place in it, and the influence one can have on it. It depends in part on how we answer the twelve questions listed earlier.

People with a low sense of fate control act as if the world were a collage of happenings with few connections between them, as though each event had sprung uninvited into their lives. The world for them is unpredictable, like a game of chance. As a rule, their knowledge and understanding of science tend to be rather primitive, if not totally absent. This lack of knowledge gives license to their belief that nothing is worth any sustained planning, since the world is in the grip of powerful forces and people beyond influence.

People with a high fate-control outlook function as if they believed that events have roots that evolve by processes they can discover and thereby possibly influence. People of high fate-control orientation are more keenly attuned to cause-and-effect and to the structure of relationships between events and ideas. Because they believe that the future grows out of what one does in the present, they are more disposed to participate in long-term plans and projects. Table 1 contrasts high and low fate-control perspectives on the world; there may, of course, be many gradations between them.

The world views encapsulated in the terminology of fate control extend over two major domains of knowledge. On the one hand, there are social phenomena. To the extent that people understand something of their nature and think of themselves as able to influence others, their ability to function effectively in complex social and economic institutions is increased.[17] On the other hand, there are phenomena, such as are encountered in the natural sciences and the explanatory systems, upon which the progress of a scientifically and technologically sophisticated world depends. The two domains intersect at the point where science is brought to bear in the service of health, technology, conservation, and other areas. As Figure 1 suggests, the natural and social sciences provide a substrate out of which young people could compound answers to their questions that would help to cultivate a world view that is more highly fate-control oriented. And if the study of ethics is included in their education, the probability that they would develop a high fate-control perspective is greatly increased.[18]

To illustrate how reasoning differs among children with low fate-control orientations as compared to high, consider the following anecdote from early research on this topic.[19] In two elementary school classrooms in two different schools, students were divided into groups of four. Each group had a small aquarium with six or seven

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TABLE 1. Characteristics of Low-Fate and High-Fate Control Views

Low-Fate	*High-Fate*
Chance—can't influence odds	Can influence odds
No use to try—you can't make a difference	Try things—learn from experience
Little prior evaluation of possible consequences of action	Evaluate outcomes and use information
Now-oriented—here and now rewards	Future-oriented—delayed risks OK
Low task persistence	High task persistence
School achievement lower	School achievement higher
Passive	Active
Weak problem-solving strategies	Aggressive problem-solving strategies
Susceptible to influence	Relatively resistant to influence
"How I do things makes no difference in how things turn out."	"How I do things makes a difference in what results I get."
Goal-setting is irrelevant	Goal-setting is relevant
Displaces responsibility outward	May be excessively self-blaming

guppies in it to care for over a period of several weeks. One Monday in November, they discovered, when they came to school, that many of the guppies had died over the weekend. In one class, members of several groups immediately began to argue over whose fish were dead and who owned those that were left. The response in the other class was quite different. Students mostly puzzled over why the fish had died and what *they* could do to save those that were still alive. (Over the weekend, the temperature outside had dropped, and there was no heat in the schools. The temperature change was apparently too much for the fish.)

Even among scientists, those with a higher fate-control orientation appear to be more productive,[20] since they are apparently able to tolerate ambiguity for a longer period while they examine a wider array of alternative hypotheses. Inquiry programs have a similar purpose: namely, to contrast what one knows with possible alternative interpretations, and then to take considered action (see Figure 1).

SPECIAL PROBLEMS OF ELEMENTARY SCIENCE

Perhaps one of our most serious concerns should be the virtual disappearance of science in grades one through six.[21] Children begin absorbing and creating explanations about things "scientific" when they are very young, and although some of these home-grown theories are sound, many are not. As the research repeatedly shows, mis-

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conceptions can be firmly embedded rather early in life and can block future learning. Furthermore, the research suggests that concepts and explanations must be experienced on many occasions over time and in different contexts. It was partly for these reasons that the elementary science programs developed in the sixties put such emphasis on direct experience with phenomena, on how the processes for producing knowledge are related to what we believe in science. It seems clear that exposure to science throughout elementary school would help establish more appropriate "scientific explanatory systems" and therefore lessen the need to do so much unlearning in later years. Science programs that include many simple investigations not only help develop better explanatory systems, but have a beneficial effect on language development as well.[22]

There appear to be five reasons why science is disappearing in the early grades. First, despite its substantial contribution to language development generally, science is nevertheless a low-priority subject, drowned in the back-to-basics waves that inundated most education programs in the last decade. Second, this image of science is reinforced by the fact of its usual omission in district-wide testing programs. Third, it has few advocates; if science is left out of the school week, nobody complains. Fourth, it takes more time to prepare the equipment and materials for a science lesson than it does, for example, a lesson in the social sciences, to say nothing about where the material and equipment can be left safely until the time they are needed. Yet science, if taught in the inquiry mode, requires only simple equipment and materials. Fifth, of all the major subjects in the elementary curriculum, science produces the most anxiety for teachers. School administrators say their teachers do not know enough science; teachers say the problem is twofold—a lack of time to prepare, and finding the time to put science into an already crowded school program.

AN AGENDA FOR THE EIGHTIES

In his introduction to the Carnegie Institution of Washington *Year Book '62,* Caryl Haskins says,

> greatness in a nation, like personal greatness, is a measure not only of character, not only of excellence, but also of enduring significance both in ideals and in the shape and goals of effort. In any society, but perhaps especially in our own, such greatness must necessarily be valued in coin of our own

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design and minting, whose very significance, moreover, we must ourselves determine.

It is doubtful whether a democracy can afford to leave large sections of its population ignorant of science and untutored in technology. In the long run, such a decision could undermine the political and economic viability of the nation. Knowledge of science and use of scientifically based technologies may complicate our lives, but lack of it saps our will. Thus the first of a dozen recommendations for future action would be to:

1. Extend science for general education to more students over a longer period of time.

2. Extend support for science programs on television (e.g., "Three-Two-One Contact," a science program for ten-to-twelve-year-olds produced by the Children's Television Network).

3. Examine existing books and curricula in terms of the science cycle in Figure 1, and modify or add to those so that all components of the cycle are included.

4. Examine the social studies and humanities portions of the curriculum to determine what these subjects can contribute to the implementation of a full cycle. In a cogent article, "Understanding Science as a Cultural Phenomenon," D. Christianson remarked, "The human element refers to all the unexamined forces energizing and shaping science from within and from without. It is private ambitions, corporate motives, and public goals; it is lofty purposes and public expectations; it is group loyalty and professional allegiances."[23]

5. Put existing research to work in the service of curriculum development and instruction, to close the too-great gap between current practice and current knowledge. In recent years, the problems specific to learning science have begun to be researched, and although the work is far from finished, there are some very important findings for the teaching of science, particularly the teaching of those physical science concepts that have been a source of failure for so many people. Incorporation of current research into both instruction and textbooks would produce gains in science understanding.

6. Increase the motivation to study science by making the engineering sciences and the applications side of the science cycle more visible in the curriculum, and include these practical aspects of science more frequently in classroom discussions.

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7. Involve scientists and engineers from both industry and universities, as well as science educators, in curriculum planning and in the conduct of programs for in-service science teachers.

8. Employ computers in the instructional process, not just for drill and practice, but to give students access to whole arenas of knowledge that would otherwise be missed. (Computers are patient and forgiving of mistakes, but most important, they help the student to develop a point of view essential to a high fate-control orientation: namely, they make the process of feedback far more effective than it can be under what are now standard conditions in a classroom. When programs fail to run as expected, students can control them by debugging [fixing them] based on immediate feedback.)

9. Keep in mind the twelve questions adolescents ask repeatedly as they develop their world views. Provide opportunity for discussion and use resource materials that will help them develop better explanatory systems.

10. Reorganize textbooks in light of research on *what* and *how much* really ought to be covered in a course.

11. Develop accountability procedures that reflect those aspects of the science cycle which are finally incorporated into programs.

12. Provide summer science programs for in-service teachers that allow them to learn about research currently under way in the sciences and in science education, and that provide them with occasions to participate in some way.

SCIENCE FOR A DEMOCRACY

When an American science education delegation was visiting China a few years ago, one of the members conducted a brief inquiry session for teachers so that they could catch the "flavor" of the method. The Chinese teachers did the small experiment and argued over explanations vigorously. A lot of good science emerged in the discussion, and it was difficult to draw their attention back to the reason for the demonstration. Their interest had been caught. Finally, one of them said, "But why do you do things this way? Why don't you just tell them what they are to think. That is more efficient."

Each one of us must answer that question. A saying of Chuan Tsu, an ancient Chinese philosopher, provides one answer: "The pheasant in the marshes has to take ten steps in order to get one beakful of

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food; one hundred steps for one drink of water. Yet it doesn't want to be kept in a cage. Though it would be fed like a king, it would not be happy."

In a democracy, we have to teach ourselves how to live successfully outside the cage—how to be free. Science has a place in that teaching. *How* we do it matters. *Why* we choose to do it in particular ways also matters. As Gwen Frostic, an artist and poet from Michigan, tells us in her book *Beyond Time,*

> We must create a great change
> in human direction—
> an understanding
> of the interdependency
> by which the universe evolves
> Know
> —that knowing—
> is the underlying foundation
> for the life we must develop. . . .
> We cannot leave it to the scientists—
> nor any form of government—
> each individual
> must fuse a philosophy
> with a plan of action.

We must begin the process of developing scientific wisdom suitable for our time. It can be argued, with good justification, that as the programs of science education decay, so will the potential to shape the future to our own benefit, to maintain some control of our own destiny.

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Philip W. Jackson

The Reform of Science Education: A Cautionary Tale

THE THREE FULL DECADES since World War II are an intriguing period in the history of American education, for it was during those years—the fifties through the seventies, roughly speaking—that the federal government made an extraordinary effort, unprecedented in scale, to involve itself in educational affairs for the purpose of improving the quality of schooling for a significant portion, if not all, of our nation's youth. These federal incursions into school affairs involved all three branches of government, and were expressed in judicial decisions, legislative acts, executive orders, and the policies of funding agencies. In one way or another, the impact of these efforts has been felt throughout the land, but the persons most directly affected have obviously been America's youth—the millions who have passed through our schools since World War II, those who are there now, and the untold numbers yet to attend.

Few parts of this vast governmental undertaking are more worthy of attention than the team projects whose goal was the production of new curricular materials in the key school subjects. These endeavors, commonly referred to as THE curriculum reform movement, even though reform efforts of a different sort had gone on before and have since, enlisted the talents of some of our nation's leading scholars, scientists, and mathematicians in the cause of precollegiate education, an event unique in our time. But they have now ended, or at least have come to a standstill. This seems like a natural time, then, to take stock of the accomplishments and to ponder where we might go from here.

The remarks to follow are my version of such a stocktaking. They are divided into four parts. The first is an attempt to place the curriculum reform movement within a broader context than that of curric-

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ulum alone, by relating the reforms to the total scope of federal intervention into educational affairs. The second presents some bare facts about the reform movement, having to do chiefly with the cost of the endeavor and with its actual accomplishments or its failures. The third deals with why things did not work as well as expected. The fourth takes up the question of where we go from here.

At the risk of oversimplification, federal efforts to improve our schools may be depicted metaphorically as moving in two different, but not opposite, directions. Rather, their separate tracks seem to me to be a right angle, one of whose sides is horizontal and the other vertical.

Insofar as ultimate goals are concerned, the horizontal movement of federal effort is toward equity and social justice; it symbolizes a spreading out and an evening up of goods and resources, like hands smoothening the wrinkles of a sheet or a baseball umpire gesturing a safe play. The vertical direction of federal strivings is toward excellence and heightened achievement. Like the lift-off of a rocket, its upward thrust symbolizes a going after the as-yet unattained, a probe into the unknown.

Examples of federal activities classifiable in these terms are so abundant that even the proverbial man-in-the-street could probably name several if asked. Civil rights legislation and the space program are of course the most obvious exemplars of horizontal and vertical movement. The fact that not all federal projects are as easily placed at right angles does not invalidate my point, although it does complicate it, as we shall see later.

Even within the somewhat restricted domain of federal interest in education, examples of horizontal and vertical movement abound. *Brown vs. Board of Education,* which initiated school desegregation programs, is surely the preeminent instance of horizontal movement, although the various congressional decrees that, for example, established the right to bilingual instruction, mandated the mainstreaming of handicapped students, and protected the rights of young women in school athletic programs are not far behind. All such governmental actions can, in the framework I propose, be seen as a reaching out to individuals and groups who heretofore had been treated unfairly by our school system.

Vertical movement would include scholarship programs for the training of scientists, special provisions for the education of gifted students, summer workshops to upgrade the mastery of science and

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mathematics of classroom teachers, and of paramount importance for my argument, the production of new curricular materials to replace those whose content or method is judged to be lagging behind the advance of human knowledge. The first point to be made about the curriculum reform movement, therefore, is that in my scheme, it is closer to the vertical axis than to the horizontal, closer, that is, to the line of force pointing in the direction of academic excellence and quality than to the one pointing toward social equality and justice.

The significance of this placement for understanding the past and forecasting the future of federally funded curriculum reform efforts increases with two additional features of the horizontal and vertical dimensions. The first has to do with the relative status of these two pathways of action within the federal establishment and the nation at large; the second, with compromise, conflicts, and other forms of interaction between the forces working in the two directions.

If we could somehow place into one or the other of our two categories all those federal activities bearing on educational matters—from judicial decisions to grant solicitations—I have no doubt that the horizontal container would be filled to overflowing long before the vertical made it to the halfway mark. It is crucial to keep this imbalance in mind as we strive to place the curriculum reform movement within the larger context of federal interest in education.

Despite the publicity the reforms enjoyed as they got under way, the money spent, and the retrospective attention paid to them today as educators try to figure out where to go from here, the curriculum reform movement, as initially conceived and executed, was located outside the mainstream of federal concern with education. And that stream, for quite some time now, has been moving horizontally rather than vertically.

Readers familiar with the details of several of the programs under consideration will probably complain that my depiction of federal involvement in education is far too simplistic to fit the facts, and may even be a hindrance to understanding. True enough. All metaphors are of limited usefulness, and mine is no exception. Moreover, given that the government can—and does—move in two directions at once, the directions need not inevitably be at right angles. They could in fact lie much closer to each other—at an angle of forty-five degrees, let's say, rather than ninety. Moreover, that some governmental activities seem to be moving toward both goals at once provides some justification for narrowing the angle's width.

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Two examples of such a blending are the government's efforts to attract more women and minorities into scientific careers and its support of a social studies project aimed at producing textbooks that contain a fair and just treatment of the contribution of minorities to American life. In both instances, the goal is neither equity nor excellence alone, but rather a mixture of the two.

Though there are many instances of such doubling up of purposes, there remains, nevertheless—at least in principle—a kind of natural tension between these two ends of human action. This tension is particularly evident when resources are scarce. At those times, advocates of either policy become more protective of their own interests and less willing to compromise.

Within the federal government, this tension gets worked out in several ways. It is significant that most of the curriculum reform efforts, except for those in foreign languages and English, were initiated by the National Science Foundation (hereafter NSF) rather than by what was then the U.S. Office of Education (now a department) or its field stations, the regional labs and centers.[1] The curriculum development work that does go on within the latter set of institutions is much less ambitious than the efforts in the curriculum reform movement proper, and is much more oriented toward the goal of equity than toward improving the quality of curricular offerings in the conventional school subjects.

The placement of curriculum reform efforts within NSF underscores my point about those efforts being closer to the vertical axis than to the horizontal on our hypothetical grid. For NSF is without doubt the institutional embodiment of the federal concern with intellectual excellence, at least insofar as it is manifested in scientific inquiry and research. Other federal organizations, such as the National Institutes of Health, the National Institute of Education, the National Endowment for the Arts, and the National Endowment for the Humanities, are also concerned, each in their own way, for the furthering of excellence in one form or another. But in the minds of many, NSF remains the bastion of all such efforts.

The curriculum reform movement, it seems clear, was almost from the start located off to one side of the dominant drift of governmental action. During the period when the earliest of such efforts were initiated, in the mid-to-late fifties, our national anxiety about keeping ahead of the Russians set a competitive tone that for a time placed excellence, at least in the sciences, ahead of equity. But by the time the reform efforts were in full swing a decade later, that earlier mood

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was gone, and the turn toward issues involving social reform had already taken place.

This off-to-the-side status of the curriculum reform movement is especially germane to the question of whether and how such a movement could be undertaken anew. It seems evident, from my brief overview, that this would require, at the very least, a major shift in governmental policy. Whether such a shift is currently under way is a question very much in the forefront of today's political analysis and debate.

So much has been written and spoken about the curriculum reform movement that even those who have had no direct or second-hand contact with any of the so-called new curricula have at least a vague notion of what they are like. Thus little need be added here to what is almost common knowledge. One widespread misconception, however, needs correction, before I attach a few numbers to a familiar set of generalizations. The misconception has to do with when the reforms began. Contrary to popular belief, *Sputnik I* did not start it all. A brooding dissatisfaction with what our schools were doing, combined with a deep worry about the educational accomplishments of the Russians, had been troubling the leaders of our scientific community long before the end of World War II. The seminal document in which such concerns were first voiced was Vannevar Bush's report to the president in 1945, "Science—The Endless Frontier."[2] This document, which had been commissioned by President Roosevelt in 1944, provided the basis for the founding of the National Science Foundation in 1950. It established beyond dispute an urgent national need to improve instruction in science and mathematics at all levels of education. In response to that need, summer institutes to upgrade the scientific and mathematical knowledge of high-school teachers were begun in 1954, and a grant to develop a new physics curriculum at the high-school level, the first award of its kind, was given to Jerrold Zacharias of M.I.T. in November 1956, almost a full year before *Sputnik I* streaked across the sky. Though that famous Russian achievement, and others soon to follow, certainly helped to speed the curriculum reform movement along, chiefly by loosening the federal purse strings, such events cannot be credited with getting things under way.

Some idea of just how rapidly NSF became involved in curriculum development and how extensive that involvement became is revealed in the following statistics. In 1954 NSF's total budget for curriculum

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development was $1,725. In 1955 it was $15,000. Two years later, in 1957, it had jumped to $500,000, and two years beyond that, in 1959, it had increased tenfold to just under $5.5 million. By 1968, the peak year of funding for curriculum development within NSF, the budget for that activity was just under $12,250,000. The total amount spent by NSF to fund fifty-three separate curriculum development projects from 1954 through 1975 was slightly more than $117 million.[3]

That sounds like a staggering amount of money, and by most standards, it is. Yet when placed beside the $100 billion plus that we spend on operating our elementary and secondary school systems each year, or even compared to the federal share of that amount, which is close to $6 billion a year,[4] $117 million loses its punch. It is still a lot of money, but not when compared with our total educational expenditures during the period when it was spent, and would hardly count as start-up funds today for some of the more ambitious aspects of our space program or defense needs.

What has the expenditure of those monies yielded? How have the schools changed as a result? The answers are not easy to give, for schools and what goes on inside them are notoriously difficult to study. When the classroom door is closed, as cynics are fond of putting it, no one knows for sure what is happening within—sometimes not even the teacher!

Yet fragmentary evidence concerning the impact of the curriculum reform movement *has* begun to emerge, much of it coming from three studies sponsored by NSF itself. The first is a national survey of teaching practices, including curricular adoptions;[5] the second, a collection of case studies involving intensive classroom observations at eleven school sites across the country;[6] the third, a review of the literature on the status of precollegiate science, mathematics, and social studies during the twenty-year period beginning in 1955.[7] In addition, the National Assessment of Educational Progress (NAEP) has published two reports on the scientific knowledge and the attitudes toward science of a national sample of nine-, thirteen-, and seventeen-year-old students, together with parallel data from a sample of young adults.[8] There have been countless smaller studies as well, many comparing students who have been exposed to one or another of the "new" curricula, with those who have been taught the same subject more traditionally. Using newly developed techniques of meta-analysis, a few investigators have recently begun to pore over

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the results of these small, comparative studies, in search of trends that might be overlooked when each is looked at singly.[9]

An additional set of smaller studies has attempted to tease out what might be called the secondary effects of the curriculum reform movement, including such things as the research it has spawned and its impact on commercially prepared materials.[10]

The picture that emerges from all we know so far is mixed. On the positive side, many of the federally funded materials have found their way into the nation's schools, especially science materials, as contrasted with materials in social studies and math. The NSF-sponsored survey, for example, reports that well over half of the school districts sampled were using at least one of these materials in grades seven through twelve, and 40 percent were using more than one. Usage figures are somewhat less for the elementary grades, but even at these lower levels, more than 30 percent of the districts reported using at least one of the federally funded curricular materials in the 1976-77 school year.[11]

Unfortunately, these figures do not tell us what percentage of students actually work with the materials or why adoptions were made in some districts but not in others. Nonetheless, the solid numbers these surveys supply show that the adoption of federally funded materials is rather widespread, particularly in the sciences, and especially at the higher grade levels.

And the secondary effects of these materials are evident here and there throughout the system as well. Among the most noticeable are the changes made in commercially produced textbooks. One study reports that from 1965 on, close to 70 percent of the changes made in *Modern Biology,* the most popular high-school text in the field, were made to conform with the model offered by materials emanating from the BSCS (Biological Science Curriculum Study) teams, the federally funded project in biology.[12] These changes reflect not only the updating of factual content, but also the shifts in relative emphasis given to various concepts within the field, and an increased emphasis on student inquiry and laboratory work in the learning of biology. So there is clear evidence that the federally sponsored projects on the teaching of biology pulled the commercial textbook establishment along with them, at least part way. Though hard data are still lacking for other parts of the curriculum, a similar pattern of influence will no doubt be found there.

From the hundreds of small studies that compared student performance on the "old" and the "new" curricula, the evidence finally

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emerging, via meta-analysis, says that students who studied the new curricula gained more knowledge and skills on average than did their classmates who took the traditional courses, and that the former also developed better attitudes toward science.[13]

But tucked away among the statistics that convey the good news are more sobering ones. For example, though federally sponsored materials were in use within the schools by the mid-seventies, no single project was in use in more than 25 percent of the districts surveyed, not even within the secondary schools, where the adoption rates were highest.[14] Moreover, only one set of materials—Introductory Physical Science—reached that level. Most other sets were found in no more than 10 or 12 percent of the districts.

With the possible exception of the three texts produced by the BSCS project, none of the federally funded projects could compete in popularity with the most successful commercial texts. In 1974, for example, *Modern Chemistry,* published by Holt, Rhinehart, and Winston, was used by about 50 percent of the students studying chemistry.[15] Even at its peak, the federally sponsored *CHEM* did not come close.

The story in math is even more discouraging. None of the materials in that subject ever fared as well as did those in the sciences. In 1977 no federally funded math materials were in use in more than 5 percent of the districts surveyed.[16] It should be emphasized, however, that these statistics say nothing about the secondary impact of the mathematics projects, which at least one leader in mathematics education claims to have been considerable.[17]

To round out this discouraging picture, the NSF-sponsored survey shows that the adoption rates for the federally sponsored materials peaked in the early 1970s and have been on the decline ever since;[18] it shows, too, that the percentage of students enrolled in high-school biology, chemistry, and physics also peaked at about the same time, and is now less than it was a few years past.[19]

At the elementary level, these materials seem to be even less well established than in the high schools, perhaps because science and social studies have never occupied a prominent place in the elementary school curriculum. One study, for example, reports that not until the fourth grade do students spend more than twenty minutes per day in science and social studies.[20] Even in grades four to six, only slightly more than a half hour per day is spent in those subjects.

But this does not tell the whole story, for in mathematics, a subject that *is* prominent in the lower grades, the federally sponsored materi-

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als do not appear to be in wide use. Only 8 percent of the school districts surveyed reported using one or more such materials.[21]

When we add to these statistics the squeeze that the "back-to-basics" movement has put on the time available for science and social studies in the elementary curriculum, together with the insistence on accountability and competency-based testing, we find we have small cause for cheer.

Yet the statistics on adoption rates are not the only source of worry. There is also the question of which aspects of the new programs are being adopted. The goal of most of those programs was two-pronged: to update the content of the subject matter, bringing it in line with what is now known about scientific matters, while at the same time introduce students to the process of science as actually performed by its practitioners. This second aspect called for the extensive use of laboratory equipment and other forms of "hands-on" experiences, and the term "discovery method" was thus an altogether appropriate label for this set of pedagogical strategies.

The little we know about how the materials are actually being used in the classroom suggests that one half of this two-pronged goal is being partially fulfilled and the other not. Today's students are now being exposed to content that is more factually correct, in the sense of being closer to what leading scientists claim to know, than was true in the past; yet the new material is still being taught in "old" ways, with an emphasis on recitation and the memorization of facts.[22] The notion of science as a process, a *mode* of inquiry, seems not to have caught on, even among those using the inquiry-oriented materials. Paul Hurd, a leading authority in science education and one of the authors of the BSCS materials, summarizes the problem succinctly: "For most teachers, science is still a noun, not a verb."[23]

The final note in this report on the downside of the curriculum reform movement is that of public controversy, especially over the inclusion of sensitive topics, such as sexual reproduction and the theory of evolution, in some of the instructional units. The storm of criticism over the publication of the social studies project *Man: A Course of Study* led to soul-searching within NSF, and contributed significantly to the curtailment of congressional support for curricular projects.[24] It would be an exaggeration to say that such criticism sounded the death knell for the curriculum reform movement, but it clearly contributed to the gloom now felt by many of its early enthusiasts.

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Paul Hurd, for one, describes the curriculum field as being "in the doldrums."[25] Jerrold Zacharias, the first and perhaps best-known participant in the reform movement, speaks of "today's deadening sense of frustration and near defeat," and laments "the present atmosphere of despair and confusion."[26] Thus, whatever else might be true of the curriculum reform movement, one disheartening conclusion seems incontrovertible: it did not live up to expectations.

Although reform movements throughout the ages have never accomplished all that their designers had optimistically, perhaps unrealistically, hoped for,[27] a close look at the curriculum reform movement reveals that things did not work out as planned for at least three major reasons intrinsic to the movement itself: (1) the level of difficulty of the materials produced; (2) the complexities of their dissemination; and (3) the ambiguities surrounding federal policy with respect to curriculum development.

The most common charge leveled against the new curricular materials—hence, the most popular explanation of their low adoption rates—is that many were simply too difficult for teachers to teach and for students to study. The problem on the teaching side was twofold. First, many teachers, particularly in elementary and junior high schools, but including many in high schools as well, did not have sufficient training in science and math to handle the new materials.[28] Although the special in-service training programs and summer institutes that were created to address this problem had some small success,[29] the lack of teacher preparation continued to militate against the widespread adoption of the new materials.

Second, the new curriculum placed heavy emphasis on so-called discovery methods, many of the projects calling for active student involvement in the learning process far beyond their usual participation in the typical question-and-answer exchange with the teacher. Materials were to be handled, experiments conducted, projects undertaken. The orchestration of all these activities in classrooms with twenty-five or more students, it was claimed, was simply too much for the average teacher to handle. Another commonly heard complaint was that the materials were given directly to practicing teachers, rather than to "teachers of teachers," thus effectively skirting the teacher education establishment whose so-called methods courses were commonly lampooned and sometimes pointed to as the source of much of the difficulty. Newly trained teachers thus entered their classrooms totally unfamiliar with the materials awaiting them.

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And there were, of course, the usual assortment of mechanical problems. Equipment had a way of breaking down or being lost or vandalized just when it was needed most. Beyond the pedagogical frustrations occasioned by such breakdowns and losses, there were the costs of repair and replacement, which often turned out to be prohibitive.

On the learning side, the chief complaint was that most of the high-school curricula were designed for college-bound students—and extremely able ones at that—and principally for those headed for scientific careers. This "preprofessional" cast made many of the materials unfit for students of only average ability, and unattractive to those whose interest in science was not very keen to start with. Even the materials for the elementary grades, the complaint continues, were beyond the reach of the average youngster, to say nothing of those below average.

Given the scientific community's concern about the nation's future supply of scientific talent, the intellectual brillance of many of the scientists who worked on the materials, and the virtual absence of educational practitioners on the project teams, it is easy to see how this bias was built into the material. And when practitioners did offer suggestions to the scientists, they were not often heeded.[30] At the high-school level, the problem was exacerbated by an elective system that allowed students to opt out of "tough" courses. Thus, whether the new material was really as difficult as claimed is partially beside the point. That many students *perceived* it as being too demanding very likely contributed to its relative lack of success.

A second reason more of the materials did not find their way into classrooms grows out of the failure of those in charge to comprehend the complexities of schools as institutions, and in particular, their unawareness of how curricular decisions are made in most schools. Thus they believed—naively—that the materials' unusually high quality, to say nothing of the intellectual prestige of many of the project team members, would be reason enough to ensure their adoption.

Seldom did any of them venture to assess such matters as statewide textbook adoption policies, the competitive pressure of the textbook industry, the impact of standardized testing programs and college admissions policies, the role of the school administrator as a catalyst or inhibitor of change, the conservative influence of teacher certification requirements, and so on.[31]

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Nor were they prepared for the resistance that would be encountered, both within the schools and from the public at large. The controversy that flared up over *Man: A Course of Study* was only the most dramatic instance of public resistance; there were as well a great many complaints over the inclusion of evolutionary theory and sexual reproduction as topics in some of the materials. Flare-ups would have occurred in any event. It is just that, having failed to test public opinion, both the curriculum-makers and the funding agency were caught completely off guard by the attacks, stunned by the fact that anyone might seriously object to what they were doing.[32]

This surprised reaction to controversy on the part of the funding agency, together with a certain awkwardness in dealing with it, is symptomatic of a deep and fundamental uneasiness about whether curriculum development is the business of the federal government at all. Thus, ambivalence on the part of government leaders is yet a third explanation for the somewhat limited success of the curriculum reform movement. Many government leaders wanted very much to contribute to the improvement of our nation's schools. Yet many others wanted—just as strongly—to avoid governmental meddling into what they believed were the most private of all affairs, the mental states—including knowledge, skills, and attitudes—of citizens, especially the young. The very notion of a national curriculum, with its Orwellian threat of thought-control, was a spectre that haunted them.

Thus the problem became one of accommodating these conflicting hopes and fears. Within the curriculum reform movement, the solution to that problem took many forms, none more interesting than the federal approach to the question of how to disseminate the materials without at the same time foisting them on an unwilling public.

One solution was to fund not one, but several different projects within each subject matter area. This would allow potential users to choose from among a set of competing materials, thus avoiding any suggestion that the government was forcing a curriculum on the schools, while at the same time acknowledging that there *was* more than one way of presenting a subject like biology or chemistry. The rationale for this approach is succinctly stated in an NSF brochure advertising the projects under way. "Decisions on what to teach," the brochure announced,

> remain in the healthy American tradition an exclusive responsibility of individual schools and teachers. The National Science Foundation does not rec-

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ommend the adoption of any specific book, film, piece of apparatus, course or curriculum. It is hoped, however, that the products of these projects will prove to merit serious consideration in every school and college.[33]

Though it might have been based, as claimed, on "a healthy American tradition," the government's position was difficult to maintain all the same. To behave as the government thought proper was somewhat like acting the shy salesman, who sets his wares out and then retires to the checkout counter, where he awaits his customers. If, in the meantime, someone should ask him about the merits of this or that product, the poor fellow can but shrug his shoulders and smile. All he can say is that everything in the store is of uniformly high quality.

An additional source of ambiguity and confusion had to do with who would produce and distribute the curricular materials. Given our high regard for the free enterprise system, "the American textbook industry" may seem like the natural answer, but it made government officials nervous for several reasons. They worried about companies making large profits from the sale of materials whose initial development was paid for by taxpayers. At the same time, they did not want to do anything that might prohibit the making of a fair profit, for fear that commercial firms would lose interest in the project. Also, they were reluctant to interfere with the unconstrained play of market forces for fear of being perceived as an enemy of the free enterprise system. Finally, their desire to maintain impartiality made them leery about entering into any partnership that might make it look as though one or more firms were favored over some others.

This complex set of considerations led to much waffling and indecision. Consider, for example, the juggling of concerns about favoritism, taxpayers' interests, and the wish for the materials to be disseminated ultimately by commercial firms. One way to avoid favoritism, it was argued, would be to make the materials available free of charge to any commercial firm that wanted them–though this would mean giving away what taxpayers had paid for. Also, it soon became obvious that if the materials were simply placed in the public domain, free for the taking, publishers would avoid making use of them for fear that competitors would come out with identical products at marginally lower costs. The result could well become a price war, dashing all hopes of any publishing company making a reasonable profit. The complicated and unstable set of commercial distribution

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policies that grew out of this tangle of considerations further explain why commercial interest in the projects was limited.[34]

So much, then, for what seem to be at least three major reasons why things did not go as well as planned. Certainly, other forces were at work, too—the Vietnam War, student unrest, and declining school enrollments are among those commonly mentioned in connection with a waning interest in science and mathematics in recent years—but the three I have touched on, although surely not the only cause for the less than hoped-for results of the curriculum reform movement, were contributing factors of no little significance. The only question that remains now is, Where do we go from here?

The first step in determining new directions in curriculum reform is to formulate the problem a little more precisely than has been done so far. We know it has to do with the quality of math and science instruction in our public schools. We know, further, that American students are not doing as well in these subjects as many people believe they can and should do. Beyond that, we know that the new science and math curricula did not succeed in correcting this state of affairs, and in some ways perhaps added to it. But what exactly is the difficulty? Does the fault lie with the teachers or the curriculum, or is there something in the entire school system that needs correction? Might other impediments, having little or nothing to do with the schools, stand in the way? Until we can answer questions like these a little more fully, a remedy for the situation (assuming there can be such a thing) will continue to elude us.

In the interest of answering such questions, while at the same time soliciting suggestions about what to do next, NSF itself sought numerous reactions to the three status studies it sponsored.[35] In addition, under the collaborative undertaking named "Project Synthesis," NSF brought together twenty-three educators and science teachers for the purpose of interpreting not only the NSF-sponsored studies, but also the two NAEP reports on scientific knowledge and attitudes toward science among school-age youth.[36] In addition, there have been at least two federally funded conferences on the subject,[37] plus one sponsored by two private foundations held at Phillips Exeter Academy.[38] Many evaluations and recommendations from individuals have also appeared in professional journals over the past few years,[39] and editorial comment in both the professional and the popular press is too abundant to tally.[40]

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Though the different reactions are considerably diverse, almost all agree on the two goals toward which the efforts of all concerned—from private citizens to officials of the federal government—should be directed: *more* science and math instruction in our schools, and *a different kind* of science instruction at all levels, but especially in the upper grades and beyond.[41]

There is also widespread agreement on what is needed, in general terms, to accomplish these goals: a nationwide campaign, enlisting the help and support of almost everyone, from classroom teachers to congressmen, from the proverbial man-in-the-street to the Nobel laureates of the scientific community.

Neither of the goals will come as a surprise to anyone, nor will the plea for a concerted effort to achieve them. But if we look a little closer at each goal, beginning with the second—for the simple reason that it may well hold the key to the partial attainment of the first—we will see that both are quite complex, no matter how simple and straightforward the rallying cries of "More science!" and "A different kind of science instruction!"

To begin, in what way must science instruction be "different"? In a phrase, it must be "science for all," as opposed to "science for future scientists." Everyone by now seems to agree that a major fault of the NSF-sponsored science curricula was that they were too "preprofessional." They were, that is, not only too difficult for the average student, but were characterized by a singleness of purpose, and that purpose was to ready students for college-level science and beyond.

The desired new science instruction will not be so much "easier"—though that is certainly part of it—as it will be science "brought to life," science taught in a way that will make apparent its relevance to daily living and to current social issues.[42] And it will be "science through thought and action," science taught through laboratory and field experiences that stress the skills of inquiry, problem-solving, and decision-making, as opposed to the mere collection and memorization of scientific terms and facts.

Exactly how much of a change the first suggestion calls for is not entirely clear. Some proponents talk as though all that is needed is for teachers to begin discussing contemporary issues in their classes, using them as examples, setting aside time for class discussions, and so forth. Others insist that the change awaits a major restructuring of our educational priorities and an entirely new set of teaching materials. Examples of societal issues that might appropriately be treated, whether requiring new materials or not, include chemical additives to

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foods, genetic engineering, pollution, energy conservation, and the disposal of chemical wastes.

The insistence on science teaching that stresses "current issues" and the "personal needs" of students cannot but evoke those heady days in the sixties, when the call for "relevance" in the curriculum was carried to excess in many schools and colleges. Some educators doubtless fear that the same thing could happen again. Yet science that is made more appealing to the average student can also be "good" science. And although the schools have been accused of "sugar-coating" and "watering-down" the curriculum with every move to make learning a more palatable and engrossing experience, such accusations have often turned out to be unwarranted. It will tax the ingenuity of our most talented and dedicated teachers and textbook writers, for some time to come, to make the new science education a solid learning experience.[43]

When we turn to the implementation of the so-called inquiry methods, we encounter a different and perhaps more difficult problem, for these were precisely the methods advocated by the science curricula of the recent past and rejected by teachers for a host of reasons, ranging from broad managerial problems to mundane matters such as the loss of equipment through breakage or theft. Will a renewed call for such "progressive" methods of teaching stand any better chance of being adopted this time around? Probably not, because the difficulties remain. What this says about the goal of getting students to "think scientifically" or to apply "the scientific method" to their own lives is a question to which I shall return.

The first of the two goals, that of having more high-school students enrolled in science classes, is at least partially dependent on how successful teachers are with the second, "bringing science to life." The logic linking these goals is incontrovertible, for if science is made more attractive, more high-school students will elect to study it. Yet this expectation is not sufficient to allay the concerns of some critics, who insist that the schools and our nation as a whole cannot afford to bank on more science being called for by popular demand. In addition to improved courses, they say, we need *requirements* mandating an increased amount of time for science in the lower grades[44] and an increase in the number of required science courses in high school.[45] But to do this will mean that the increased time or course credits must necessarily displace something else in the school day, because the amount of time spent in school is fixed and has not changed greatly over the past several decades. Thus the bid for more

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science instruction is almost certain to set off an internecine struggle for curricular "turf," particularly above the elementary grades, where most teachers are subject matter specialists. Unless those who argue for more science also insist upon a longer school day or a longer school year, their objective, if it is attained, will mean less of something else, even if nothing more than a shortened lunch hour or a forgone study period.[46]

There is also the question of who will teach these courses, since many parts of the country are already suffering a shortage of science and math teachers. Over the long haul, market forces will undoubtedly produce the needed supply of teachers, as they have done in the past, but in the face of the current critical teacher shortage in the sciences, it is not clear how we will begin to move toward this goal.

On the methods of achieving the two goals, there is nearly unanimous agreement on the necessity of a broad campaign carried forward on many fronts, with something for everyone to do. Among the suggestions that have been made so far, are the following.

- Classroom teachers should begin immediately to enliven their instruction by emphasizing the connection between science and everyday affairs.
- Textbook writers must follow suit by developing new institutional materials reflecting the same change in emphasis.
- Professional organizations must help broadcast the alarm, bringing the problem to the attention of the public, while enlisting the support of their own membership in seeking a solution.
- Teacher educators are urged to strengthen the science component in training programs for teachers.
- Private foundations need to help identify exemplary science programs and outstanding science teachers so that others might learn how to improve their own practice.
- School systems must create new supervisory positions, placing within each system, if not within every school, a "science resource specialist" to help advise teachers on how to improve their science instruction.
- The federal government must develop a "sensing system," more extensive and elaborate than the current NAEP, with the explicit function of keeping the nation informed about the state of science instruction.

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- Summer institutes should be established once again, to keep classroom teachers up-to-date in their understanding of science and to introduce them to new curricular materials.
- Federally supported centers at which the most current programs and instructional strategies could be observed might well be another means for keeping teachers up-to-date.
- Conferences, sponsored by a wide variety of funding agencies, are needed to bring together science teachers, practicing scientists, government officials, and others for the purpose of combining many different perspectives in search of a solution to the problem.
- Directors of museums and managers of public radio and television are urged to bring the problem to the attention of a wider public and to help supplement the instructional capabilities of the schools.
- Private industry must do its part by offering summer jobs to science and math teachers to augment their income, thus enabling them to remain as classroom teachers rather than taking higher-paying jobs elsewhere.

The point of this list, which is by no means complete, is to show that not only is the call to action quite broad in scope, but that much of what needs to be done is sensible, down-to-earth, and can be acted on with little fuss and bother. Some of the points, of course, will not be quite so simple to effect.

What the list fails to give, as do also the supporting arguments accompanying the recommendations, is the true scope of the problem, fails to show that it extends far beyond the teaching of science and mathematics. Yet the absence of that vision is not quite total, for in its review of the NSF-sponsored studies, a panel representing the American Association for the Advancement of Science concluded that "the time is ripe for an in-depth examination of the goals and purposes of precollegiate education" and spoke of the need for "a *reaffirmation of concern for quality* in education."[47] And a panel representing the National Academy of Science and the National Research Council acknowledged that the evidence from the three studies commissioned by NSF points to "a troubled American school system."[48] But by and large, those who seem to be most up in arms about what should be done next rarely worry about the state of the total system. Their concern seems fixated on the math and science portions of the curriculum and what can be done to improve them.

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Given the backgrounds and vested interests of those who are most upset about the current state of math and science instruction, their concentration on a piece of the curriculum rather than the whole of it is understandable—but lamentable all the same. By neglecting to consider how widespread the problem of inadequate instruction and a weak curriculum might be, the advocates of more and better science and math run the risk of cutting themselves off from the much needed support of what could become a veritable army of allies—thousands of teachers, school administrators, university professors, concerned citizens, and others—who have almost precisely the same concerns with respect to *other* subjects and *other* portions of the curriculum, and with the way the schools are run in general.

Dull courses; instruction that bears no relation to the concerns and interests of students; emphasis on the memorization of facts and the consequent neglect of critical thought; half-hearted teachers; petty administrative practices—the history of educational criticism in this century, and long before, reminds us that these defects are by no means restricted to math and science alone, but are endemic throughout the system and have been for generations.

But here, a cautionary note. This litany of complaints is not a blanket indictment of our schools, nor does criticism of math and science instruction imply that all is lost there either. A lot of good things are happening in America's classrooms, in every subject and at every grade level. No one who has visited extensively in our schools in recent years, as I have, can fail to acknowledge that for every defect there are corresponding strengths: exciting courses; instruction tied to the concerns and interests of students; emphasis on critical thought and the consequent deemphasis of memorization for its own sake; enthusiastic teaching; bold and imaginative administrative practices. These are there as well, and have been for generations, as the history of educational innovation and the testimony of former students so eloquently bear witness.

The broader question becomes one of how to rid the system of what common sense alone tells us should go, while preserving and strengthening what the best teachers and the best administrators have been practicing for some time. Easier said than done, no doubt, and not something that any single group, bent on reform, can accomplish alone. All who care deeply about the sorry state of science and math instruction in our schools should be encouraged to join forces with those who care as deeply about other subjects and how well they are being taught. These two groups, in turn, must fall in step

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with enlightened administrators and others who are responsible for the well-being of the total enterprise. What is needed is a sense of partnership, an awareness of common cause uniting *everyone* who seeks to see our schools become better than they are.

Some division of labor is certainly inevitable and highly desirable as well, for to be effective, all large work forces require some degree of specialization. At the same time, we must be careful to avoid having these divisions become divisive as well, by pitting science or math teachers and their supporters, for example, against those who teach other subjects. One and all must realize that *good* science teachers have more in common with, say, *good* English teachers, and vice versa, than either does with mediocre or poor teachers within their own specialties. Similarly, conscientious administrators have more in common with like-minded teachers than either does with administrators or teachers who are derelict or lackadaisical in the performance of their duties. In sum, the primary loyalty of everyone connected with our schools needs be to the *quality* of the educational service being provided, rather than to this or that portion of the curriculum, or to this or that institutional role.

Finally, there remains the question of whether the "inquiry," or "discovery," approach to the teaching of science might fare any better in the future than it has in the recent past. Moreover, if—as I tend to believe—it does not, what does that say about the school's ability to foster "scientific thinking" and "a scientific attitude" among students?

Science taught by textbooks, even when supplemented by films and classroom demonstrations, does leave much to be desired. It is of doubtful value compared to science teaching that makes use of laboratory work, field studies, and other forms of "hands-on" experience. James B. Conant observed that

> the stumbling way in which even the ablest of scientists in every generation have had to fight through thickets of erroneous observations, misleading generalizations, inadequate formulations, and unconscious prejudice is rarely appreciated by those who obtain their scientific knowledge from textbooks.[49]

The experience of "doing" science, experiencing its frustrations as well as its excitements, is one of the most important things sacrificed in the textbook-plus-recitation method of teaching.

At the same time, as essential as laboratory work, field trips, and all the rest of it might be to the teaching of science, it would be a

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mistake to believe—as some advocates of science instruction seem close to at times—that science is the sole vehicle within the school for conveying the skill and the habit of clear thought and rigorous argumentation. The conjoining of the ideas of scientific method and intellectual rigor became prevalent during the Enlightenment, and to this day, many continue to describe as "scientific" almost any mental posture that stands staunchly opposed to superstition, dogma, sentimentality, unbridled enthusiasm, and just plain muddled thinking. Among educational theorists, John Dewey was probably the most prominent advocate of the view that "scientific method," as he called it, and the principles of "inquiry"—his favorite term for reflective thought—were really one and the same.[50]

But Dewey's insistence on labeling as "scientific" such things as open-mindedness, intellectual honesty, impartiality, objectivity, and so forth, though perhaps in step with the thinking of his time, is quite off the mark with respect to the way such characteristics are increasingly thought of today. So, too, are all who persist in pinning their hopes for the development of those very same attitudes and intellectual qualities on what students pick up during that small fraction of their school experience devoted to instruction in science and mathematics. This is not to say that open-mindedness, objectivity, and all the rest of it are not among the hallmarks of scientific thought the world over. Of course they are. Nor is it to suggest that instruction in science and math can make no important contribution to the development of those qualities among the young. Of course it can.

It is to insist, however, that scientists and mathematicians have no corner on the techniques of sound reasoning and clear thought, nor do science and mathematics teachers stand alone as purveyors of the kind of tough-mindedness that has become historically linked to the emergence of a scientific world view.[51] Teachers of many other subjects are there to help as well. All share the common goal of seeking to extend the powers of critical rationality in the students under their care. The whole world has a stake in how well that job is accomplished.

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[9]See, for example, James A. Shymansky and William C. Kyle, "The Era of Inquiry Learning: How Effective Were the Science Curricula of the Sixties?" Xeroxed ms. 21 pp. n.d. A summary of this report appears in William C. Kyle, Jr., James A. Shymansky, and Jennifer M. Alport, "Alphabet Soup Science: A Second Look at the NSF-Funded Science Curricula," *The Science Teacher,* November 1982, pp. 49-53.

[10]See, for example, Paul DeHart Hurd, "An Exploratory Study of the BSCS Secondary School Curriculum materials," *The American Biology Teacher* 38(2) (February 1976): 79-85.

[11]Stanley L. Helgeson, Robert E. Stake, Iris R. Weiss, et al., *The Status of Pre-College Science, Mathematics, and Social Studies Educational Practices in U.S. Schools: An Overview and Summaries of Three Studies,* stock no. 038-000-00383. (Washington, D.C.: U.S. Government Printing Office, 1978).

[12]Suzanne Kay Quick, "Secondary Impacts of the Curriculum Reform Movement: A Longitudinal Study of the Incorporation of Innovations of the Curriculum Reform Movement into Commercially Developed Curriculum Programs," Ph.D. thesis, Stanford University, 1977.

[13]Kyle et al., "Alphabet Soup Science," p. 52.

[14]Saville Davis and Jerrold Zacharias, *We Need Good Schools—How to Go about It* (Newton, Mass.: Educational Development Center, 1979), p. iv-1.

[15]Helgeson, Blosser, and Howe, *The Status of Pre-College Science,* vol. 1, p. 28.

[16]Helgeson, Stake, Weiss, *et al. The Status of Pre-College Science.*

[17]James W. Wilson, personal communication, April 10, 1979.

[18]Helgeson, Stake, Weiss, et al., *The Status of Pre-College Science.*

[19]Helgeson, Blosser, and Howe, *The Status of Pre-College Science.*

[20]Helgeson, Stake, Weiss, *et. al., The Status of Pre-College Science,* p. 12.

[21]Ibid., p. 8.

[22]Stake, Easley, *et al. Case Studies in Science Education,* vols. 1 and 2.

[23]Paul Dehart Hurd, personal interview, February 2, 1979.

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[24]"The National Science Foundation and Pre-College Science Education."

[25]Paul DeHart Hurd, personal interview, February 2, 1979.

[26]Davis and Zacharias, *We Need Good Schools,* pp. 1-27.

[27]There is an additional explanation that is sometimes offered for the failure of governmental undertakings in our country: designers of large-scale projects requiring huge amounts of money are practically forced to oversell their proposals if they are to win the backing of Congress and receive the necessary funding. Among other things, this means promising more in the way of success than the proposers themselves believe can be delivered. This leads us to suspect that the curriculum designers knew all along that their products would never win national acceptance, but they had to pretend otherwise in order to obtain the necessary funds. The trouble with such a *post hoc* explanation is that there is no way of checking its validity. It is further weakened by the fact that the expressions of disappointment come from the reformers themselves and not just from those who were allegedly "oversold" on the prospect of the reform's success. It is possible, of course, to accuse the reformers of not being genuine in their expressions of disappointment, but their integrity as outstanding scientists and science educators makes that accusation absurd.

[28]Helgeson, Blosser, and Howe. *The Status of Pre-College Science,* vol. 1.

[29]Stanley L. Helgeson, "Impact of the National Science Foundation Teacher Institute Program," Ohio State University, December 1974, mimeographed.

[30]Wayne W. Welch. "Twenty Years of Science Curriculum Development: A Look Back," *Review of Research in Education* (1979): 282-306.

[31]Crane, "The National Science Foundation and Pre-College Science Education."

[32]Ibid., p. 181.

[33]Gardner, "A Brief History of Federal Involvement," p. 29.

[34]Crane, "The National Science Foundation and Pre-College Science Education," p. 82.

[35]The replies to those studies from panels of experts representing several professional organizations appear in *What Are the Needs of Precollege Science, Mathematics and Social Science Education? Views from the Field,* National Science Foundation, SE 80-9, Washington, D.C., n.d.

[36]*What Research Says to the Science Teacher,* vol. 3, edited by Norris C. Harms and Robert E. Yager, Washington, D.C., National Science Teachers Association, 1981, NSTA stock no. 471-14776.

[37]Several papers from the first of these two conferences appear in *Value Conflict and Curriculum Issues,* edited by John Schaffarzick and Gary Sykes (Berkeley, California: McCutchan, 1979). The other, held in May 1982, is reported on in *Science and Mathematics in the Schools* (Washington, D.C.: National Academy Press, n.d.), LC no. 82-61746.

[38]The conference was named the "Exeter Conference on Secondary School Science." A booklet reporting on its outcome was published by the Trustees of Phillips Exeter Academy in 1980.

[39]A representative sampling of such recommendations takes up a large portion of a recent issue of *Educational Evaluation and Policy Analysis* 3 (5) (September-October 1981).

[40]See, for example, Frank Press, "The Fate of School Science," *Science* 261 (4) (June 1982): 1055. Also, John Walsh, "Science Education—Deja Vu Revised," *Science* 216 (28) (May 1982): 963.

[41]Whether a similar change is necessary in math instruction is not clear.

[42]"Scientific literacy" is the term most commonly used to describe the goal of such a curricular change. See, for example, Edward B. Fiske, "Wiping Out Scientific 'Illiteracy,' " *New York Times,* Tuesday, December 14, 1982, p. 17.

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[43]For an interesting report on one scientist's attempt to meet that challenge, see Jeremy Bernstein, "Science Education for the Non-Scientist," *The American Scholar,* Winter 1982/83, pp. 7-12.

[44]In its position paper on the subject, the National Science Teachers Association recommends a minimum of one-and-a-half hours per week of science for the lower grades (K-3), two-and-a-half hours per week for grades four to six, and one hour a day for at least two academic years in grades seven through nine. See "Science-Technology-Society: Science Education for the 1980s," Washington, D.C., National Science Teachers Association, 1982, p. 3.

[45]The NSTA calls for a minimum of two years of science for all high-school students. Ibid.

[46]One way around this difficulty might be to combine instruction in science with instruction in other subjects, through the creation of curricular offerings that cut across subject matter boundaries. This is by no means a new idea, as anyone with a smattering of educational history in his background will quickly attest. The goal of an "integrated" or "correlated" or "unified" curriculum was among the rallying cries of the progressive education movement during the early part of this century. Moreover, that goal was more than a mere slogan. Its espousal has led to the development of some noteworthy interdisciplinary course offerings over the years, particularly in high schools and colleges. Today's "social studies" and "language arts"—the former combining what used to be history and geography, the latter covering what used to be handwriting, composition, spelling, and grammar—remain an enduring curricular innovation (though not universally admired!) of the Progressive Era.

Yet for reasons having to do in part with the way knowledge is organized at the highest reaches of education, and in part with how much an individual teacher (or even a team of teachers) can be expected to master, today's interdisciplinary curricular offerings remain the exception rather than the rule. Could that situation change in the future? Possibly so, but those who want more science taught in our schools would be foolhardy to pin their hopes on such an eventuality.

[47]National Science Foundation, *What Are the Needs in Precollegiate Science,* pp. 55, 74.

[48]Ibid. p. 79.

[49]James B. Conant, *Science and Common Sense* (New Haven: Yale University Press, 1951).

[50]See, for example, Dewey's *How We Think* (Lexington, Mass.: D.C. Heath and Company, 1932). A related but weaker view is voiced in Karl Pearson's observation that "modern science, as training the mind to an exact and impartial analysis of facts, is an education specially fitted to promote sound citizenship," *The Grammar of Science* (London: W. Scott, 1892).

[51]For a forceful defense of the continuity between the sciences and the humanities, particularly with respect to the kinds of reasoning and argumentation each employs, see Stephen Toulmin, "The Construal of Reality: Criticism in Modern and Postmodern Science," *Critical Inquiry* 9 (1) (September 1982): 93-111.

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J. Myron Atkin

The Improvement of Science Teaching

As the science education policy atmosphere heats up, and as government and industry contemplate new initiatives to improve science teaching, it is not always clear that the suggested solutions address actual problems or that the proposals have much promise of success. If salaries are increased for science teachers, will there be an improvement in the quality of those attracted to the field? If there is, will they be hired? If programs of forgivable loans are instituted for prospective science teachers to support their education, will they enter the classroom, or will they instead use their skills in industry, where starting salaries are often 50 percent higher?

While no single factor bears as strongly on the quality of science education as the ability of those who teach, and while efforts to recruit and retain the nation's most able people as teachers are of overriding importance, it is necessary to understand the factors other than money that influence the attractiveness of teaching as an occupation. The most effective policies for the improvement of science teaching will be based on knowledge of the nature of classroom teaching, the scope it does or does not accord talented people, how it is seen by those contemplating a classroom career (or leaving one), and what qualified teachers who may be attracted by the new plans are actually assigned or expected to do.

First, what is science teaching like? What actually happens in the science classroom? There is useful information about the number of teachers being prepared, the general nature of the science curriculum, and test scores, and the various data-gathering agencies are getting better at collecting such information and conveying it to the public. But what is known about science teaching once the classroom door is

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shut and teachers meet with children? What satisfactions are derived by those who choose to teach? And how does such knowledge illuminate policy choices?

The most recent intensive study of science classrooms was completed in 1978, under the direction of Robert E. Stake and Jack A. Easley, Jr.[1] About two dozen observers concentrated on a dozen high schools and their feeder elementary and junior high schools in different types of communities scattered around the country: wealthy and expanding suburbs in Texas, deteriorating central cities, the rural South, districts with a high percentage of children with limited ability to speak English. At each site, observations were made and interviews conducted over a period of about two months. The picture portrayed of classroom practices, of teachers and children talking to one another and among themselves, provides a personalized supplement to the statistical summaries:

A junior high-school principal:

Teachers are very uncomfortable with science. You really can't blame them. Personally, I think instruction in science should be left to the upper grades. About all you can ask for is solid preparation in reading, especially comprehension, and mathematics when they reach you in the junior high school.

A fragment of a junior high-school science lesson:

STUDENT: Mr. Parker, why does the rainbow hang together? Why don't we see a bunch of three color-spots in the sky instead of a band?

MR. PARKER: That's hard to explain. We just don't know enough to explain that. But keep thinking. That's a good question.

STUDENT: The one that really *gets* me is, why is the rainbow shaped that way?

MR. PARKER: It forms an arc because that's the only shape it could take optically. I think we had better get back to the prismatic refraction.

To the interviewer's questions later, Mr. Parker said that he "just hates it" when he can't answer the students' questions. He feels that no matter how much he prepares, their questions will reveal his inadequacy. "I wasn't trained in physical science, but I believe it is better to let students ask questions than to try to bull it through."

A parent of a high-school student:

In elementary school, kids know their parents care. The flashing bulbs at the one hundred and thirty-seven Santa's elves; mothers driving them in early for teacher help; "What did you do at school today?" at supper. But what is there in high school if you aren't a cheerleader or an athlete? What is there to take pictures of, or ask about, if your child is a level two or three student?

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A teacher:

When does a teacher have time to really think about curriculum problems? A teacher doesn't have time to teach. I have never seen so many demeaning jobs in my whole life. We spend no time together sharing ideas. I read so seldom in my field that I feel that it is terrible. Grading papers takes over fifty percent of my so-called free time. Student assistants could help file, alphabetize, score objective tests, create scoring distributions. How would you like to be fifty years old, with two professional degrees, and sit out here and watch the door for thirty minutes every morning? Why should I come in here ten minutes of eight to sit at a door?

Another teacher, same school:

I say that the senior class has ten percent college material, maximum! Sure seventy-five percent of them will *go* to college. That doesn't cut any mustard with me. We had a study a few years back that showed a lot of students who insisted on college prep programs never went to college.

Physics teacher:

I have been building up my material from different textbooks for the last four years, and I have reached my peak. I am not going to add any more. Classical physics is what I stress. They can see classical physics: these are things they can see, understand, draw a picture of. Modern physics leaves them out on a limb; quantum and relativity can't be seen, felt.

A general science class in rural Alabama. Miss Green has been teaching for two years.

"Tell us how an aneroid barometer works," she asks of a boy who uses the term.

"It's a vacuum between two plates with a spring."

Miss Green repeats and elaborates the answer to the class.

"We have another kind of barometer; what's it called?"

Someone else answers, "Column of mercury."

"What are its disadvantages?"

"Poisonous."

"Expensive."

"What is the height of mercury in the tube?" Miss Green asks.

"Thirty inches."

The tone and style of the lesson are conversational rather than rhetorical. Teacher and students do not constantly glance at the open pages of the textbook. The questions students raise seem to be from thinking about the problem rather than from the multiple-choice test.

Someone asks: "Where does the air in the tube of mercury go?"

Miss Green explains: "It's a vacuum," and she describes how the barometer is made. "I'll be doing this tomorrow and showing you, so you'll see.

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There's no air in the tube. It's a vacuum." She continues: "What did we say about mercury?"

"It's heavier than water."

"How much heavier?"

"Thirteen point six times."

Miss Green holds up a small plastic bottle in one hand. "Does this look heavy?" She passes it to one student after another. No one believes how heavy it is until she or he feels it. Once several people have felt it, she lets them pass it around, along with a smaller glass bottle. She warns: "Be careful with it. It's very expensive. Two years ago it cost one hundred and ten dollars for five pounds, and it'll be more now."

"How much is [in] there?" someone asks.

"Well, the small bottle is a fourth of a pound; you'll have to guess how much the big one is. You must be careful not to drop it because it is highly poisonous, and if you drop it, we'll lose it. And if you have any gold jewelry on, it'll go black, like my ring here. And you just can't polish it off. It forms an amalgam, and the jeweler can only remove it by agitating it very fast in a special solution."

"You can't see it," someone complains, looking at the bottle.

"I'll put some in my hand. Sit down, and I'll bring it around." Miss Green waits for quiet before continuing.

"Is it wet?" one girl asks.

"No, it's liquid metal. See, my hand is quite dry."

"Isn't it poisonous?"

"Well, it's not just absorbed straight into my skin in such a short time, but you've heard about mercury poisoning of fish in the news, haven't you?" (Several have.)

"Would it freeze?" a boy asks.

"Only at minus thirty degrees or something."

"How do you pick it up?"

"It's very difficult. As you try to pick it up, it breaks into smaller and smaller pieces." As she returns it to the jar, Miss Green issues an advance warning: "Tomorrow we're going to have an open vessel of mercury here. Don't be tempted to put your finger in it."

By this time, Miss Green has shown the mercury around the class, and everyone has had a chance to feel the weight of the bottles. For the last twenty minutes or so that remain, she returns to more formal class discussion and more directly to the text. Now she takes the lead in asking questions:

"What are the reasons for wanting daily weather reports? Can we get accurate extended forecasts? Can you *control* weather? What is climate? What do we call the scientist who studies weather?"

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The class answers promptly, and almost all seem interested and attentive, though this class, too, has two boys flicking their pencils one against the other to see which one breaks first. Miss Green quietly removes the pencils, and they subsequently pay attention.

Though some accurate and revealing general statements can be made about science teaching, clearly the character, quality, and especially the attitude toward it vary considerably from place to place, even from classroom to classroom. Hopes and expectations differ among teachers as well as among parents and children. In some schools, there is significant emphasis on academic achievement. Sometimes children engage in independent research. Often, though, the Stake and Easley group found that "science" is basically practice in reading. Children take turns reading aloud from the textbook, or they are asked to read silently, then respond to questions—mostly recalling statements from the text. In some classes, an observer might conclude that the major aim is to teach about the virtues of neatness, punctuality, silence, and taking turns in speaking; no matter where the teacher is in the lesson, it is interrupted to teach the importance of such behavior. Where one goes to school, the kinds of pressures for academic achievement that exist in the community, one's luck in assignment of teacher—all are of considerable consequence. There is inspired teaching in slums, in suburbs, and in small towns. Pedestrian instruction can be found in every school district, probably every school building. Much science teaching, particularly for those youngsters who are bound for careers in science, seems as good as it ever has been. Judging from the number of students choosing to take advanced placement courses and scoring well on the examinations, and from the comments of those who observe classrooms, many science programs are excellent.[2]

What about science for students not bound for college? Here, too, one draws conclusions with care. Yes, National Assessment of Educational Progress data reveal that there has been a decline in science knowledge, but not in biology, where scores for nine- and thirteen-year-olds increased slightly between 1969 and 1977.[3] Furthermore, the major development in American secondary education during much of the twentieth century has been the extension of schooling to ever-broader segments of the population, those with academic aspirations and many others besides. Forty percent of adults in the thirty-five to thirty-nine-year-old age group in 1939 had attended high

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school for four years. By 1979 the figure had jumped to 85 percent. College attendance has also increased markedly, not only in absolute numbers, but in percentages as well. In many states, about 50 percent of high-school graduates move on to some form of postsecondary education. It may not be particularly revealing to compare the accomplishments of the relatively new group in high school (and in college, for that matter) with the accomplishments of the more select group that used to attend. The information we have is just not conclusive enough for us to be confident that proposed new efforts to improve science education are directed toward the most troublesome issues or that they aren't aimed at targets where they would do more good.

What should be the nature of the science that is offered? Should all students receive science instruction? If so, should the purposes and content of science courses differ according to the student's abilities and academic goals? Should the same teachers teach all groups? These are questions of fundamental importance.

That employees in science-based industries should have adequate preparation in science, even if they do not contribute to the advancement of knowledge, and that the general population needs a significant level of science instruction to make intelligent decisions in a scientific and technological era, are arguments that are heard more and more frequently. But how much science is needed by an assembler of electronic components in Silicon Valley? By a salesperson in the same firm? By the business manager? Even if the general drift of the argument that there should be "better" science teaching is sound, what kind of science instruction is needed for these purposes? How much of it should be given in school?[4]

Ask the public if science should be taught to prepare youngsters for college; or to enhance their ability to get a job; or to help them grasp fundamental scientific principles; or to learn how science affects their daily lives; or to appreciate the contributions scientists have made to our understanding of the universe. The response will be that science education should do it all. This attitude is consistent with surveys about educational purposes generally. The public believes that schools should prepare people for citizenship, develop habits of thrift and punctuality, get youngsters ready for a job or for college, teach them to be better problem-solvers, help them to become better parents, prepare them with a fund of "basic" knowledge, teach them to drive safely and avoid drugs, and instruct them in the more effective use of their leisure time. Seldom is serious thought given to what

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the schools are in fact capable of doing, what they do better, or might do better, than other agencies in the community, or—particularly in a difficult economic period—which goals should take priority.

Powerful arguments can be made for many different goals, but usually they aren't, at least not in one place at one time. Policy tends to be made on the basis of the most troublesome problem during a given period. Distressed by teenage abuse of alcohol and drugs, we pass laws requiring schools to teach about those subjects. We compare our military position with that of potential enemies, and in response, make assumptions about the quality, or lack of it, of our science teaching, and then impose new requirements. We look at our industrial position vis-à-vis the Japanese, and conclude that science teaching must be strengthened in certain ways to improve the economy. The implications for science teaching are not unreasonable, but seldom are those who are responsible for improving science instruction given any indication what types of programs should be implemented, the kinds of teachers that should be prepared, or which "solutions" are most feasible and effective.

Much of today's reform fervor centers on the laudable goal of teaching the various subjects more accurately, completely, and rigorously. For most of the history of American education, however, the aim was quite different. Rather than developing an understanding of the subject to be taught, the subject was used as a vehicle to achieve other, presumably loftier purposes. Subject matter was transmitted, of course, but only incidentally.

Because high schools until World War II enrolled only small percentages of American youth, we need to look at the elementary schools to understand how science has traditionally been taught to the student of average ability. Science teaching at this level dates back to the first half of the nineteenth century. During the early period, a considerable number of science books, conveying impressive amounts of information, were published for children. The form was usually that of a story, with the family as setting. Father, mother, and children might be sitting around the breakfast table, and the daughter (yes, the daughter), observing a cloud of steam above the kettle on the kitchen stove, would offer a comment. Her question or observation seemed just what father was waiting for, because he then would launch into a short lecture about evaporation and condensation, about rain, and indeed about the physical aspects of the water cycle, all in considerable detail. In another setting, the young man of the

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family might bring in a compound flower, and the family would gather around while father, with awesome precision, identified its parts.

Almost always, however, the main point of the lesson was not to explain the scientific bases of these objects and events, but rather to point out that we owe their remarkable existence to the Deity. The structure of a housefly, for example, described in these books in fulsome detail, far surpasses the ingenuity of man—thereby proving the existence of God. These stories were designed also to teach lessons about thrift, punctuality, civic virtue, and the importance of respecting and obeying one's elders. In one story, the family is on an outing. Father has just completed a discourse on rainbows, in response to a question from one of his curious children, when the son trips and skins his knee. This event provides the occasion for father to lecture for three pages about the matter of carelessness in untied shoestrings and the importance of respecting parental authority. If son had listened to mother's repeated admonitions to tie his laces, he would not now have a bloody knee.[5]

It is difficult to discern any sequence associated with science in these books. They slide from rainbows to echoes to bees to color wheels to rock formation. Conceivably the authors considered themselves purveyors of moral tales as much as they considered themselves science writers.

In the second half of the nineteenth century, a powerful teaching movement called Object Teaching was initiated in Britain and the United States, characterized by the youngsters studying and describing objects brought to class. Object Teaching was one of the most faithful examples in the history of education of a science curriculum constructed on psychological principles. The psychology of the day was "faculty psychology," and the aim of education was thought to be the development of the various faculties of the mind, such as observation, generalization, reasoning, and memorization. The theory associated with the movement suggested that while elementary school youngsters are not capable of reasoning or generalization, they can observe and memorize. If the Object Teaching manuals that were published at the time (and some of them went through more than seventy editions) are any indication of classroom activity, youngsters or the teacher would bring in objects like rocks, metal wire, a piece of wax, stuffed birds, camphor, ivory, a mustard seed, leaves, india rubber, and various household chemicals, which the children were to describe. Listed at the back of the manual were the

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words that elementary school youngsters were expected to employ in displaying their growing powers of observation: argillaceous, astringent, acidulated, chalybeate, calcareous, ductile, effervescent, farinaceous, glutinous, gramnivorous, iridescent, laminated, ligneous, malleable, oleaginous, pulverable, pendulous, vitrifiable, unctuous, and many more. And this list was for children younger than nine! Each object, said the theory, was carefully selected to illustrate a particular property of matter. If the child was able to discern it, he or she was refining the faculty of observation. The faculty of memorization was honed when the children were asked to recall the adjectives that were used to describe the various objects.

The philosophy of the program is outlined in the preface to a widely used text for teachers published in 1876.

> The first series chiefly exercises the perceptive faculties, arresting attention on qualities discoverable by the senses; and then furnishing a vocabulary to clothe the ideas, and so fixing them in the mind, where they will be ready for reproduction when the faculty of conception begins to act. The second and third series, in addition to this, exercise the conceptive powers in recalling the impressions made upon the senses by external objects when they are removed from observation—also in leading from what has become known to what is unknown. In the fourth series, the children are exercised in tracing resemblances and differences, in drawing comparisons and recognizing analogies, thereby cultivating the power of arranging and classifying. In the fifth series, the reason and judgment are brought into activity; in tracing the connection between cause and effect, between use and adaptation, language or the power of expression is cultivated; the ideas developed in the lessons of the previous series are expressed either in simple words or short sentences; but throughout this series the pupils are required to put down all the knowledge they acquire, in the form of consecutive narrative. This plan promotes fixedness of attention during the giving of the lesson, a clear apprehension of facts and truths, and facility in arranging and expressing what has been acquired.[6]

So here, using science as a vehicle, the aim was to reach a different goal—to develop and exercise the faculties of the mind. Along the way, youngsters picked up a great deal of science information, but today's reader has difficulty detecting any particular sequence among the science topics. It is from psychological theory that one deduces which observations are relatively simple and thus come first, and which are better taught later when the child is more mature. A coffee berry comes before an orange but after an egg. Ginger follows cinnamon and comes before allspice.

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About the turn of the century we find a new emphasis and a fresh purpose for teaching science. The movement is called Nature Study, and the purpose is to glorify the rural life. As America entered the twentieth century, major problems were associated with rapid urbanization. The cities were evil, dirty, and sinful; the country pure and beautiful. Nature Study was invented at the College of Agriculture of Cornell University to encourage children to love—that is the word—nature to such a degree that they would be unhappy unless surrounded by animals and trees. Again, a considerable amount of science was taught, though there was now a drift toward the biological sciences. Books for children began to become strongly anthropomorphic—to increase their appeal to children presumably. Birds talked with the trees, and flowers talked to one another—but usually about their parts, and so again a great deal of information was conveyed. The purpose, to repeat, was to develop an emotional attachment to the country life.

Briefly, the 1920s ushered in a period during which Americans became increasingly aware of the powerful impact of science in daily life. The goal now of science teaching gradually became one of helping youngsters to understand the impact of such developments as electrification and central heating. Science texts described how refrigerators and automobiles worked. Every youngster memorized the four strokes of the four-stroke cycle gasoline engine. Experiments were performed to demonstrate how fuses work, and models built to illustrate the wiring of houses.

In the 1950s, people like Max Beberman and Robert Davis suggested that the math program commonly used in schools contained few ideas developed since 1700, and that one purpose of teaching mathematics should be the development of understandings about the field that correspond to those of the mathematician. A few years later, a similar plea was heard from scientists who were concerned that the high-school physics textbooks in use did not emphasize ideas that physicists consider important. For the first time, it appears that we had moved into a period when the teaching of subject matter might become an end in itself.

Those who have sought to improve science teaching in the recent past have concentrated on presenting all students with a picture of science that is consistent with the image held by scientists, especially academic scientists. They directed impressive efforts toward identifying the science to be taught for this purpose and how teachers should

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be prepared for it. These efforts, which dominated the post-*Sputnik* reforms, had three major facets. First, there was a reidentification of content to emphasize concepts considered basic in the course under review. The physics program developed by the Physical Sciences Study Committee emphasized topics like the nature of light: In what ways is light best conceived as particles; in what ways as waves? A main group of high-school chemistry reformers stressed the nature of the chemical bond. Biologists, in one of their several efforts, stressed a molecular view of their subject. In each of these instances, there was a winnowing of content as well as a redirection of it. Better, it was believed, to know fewer basic topics in depth than to aim for coverage. Better, also, to emphasize fundamental science than applications. Before the reforms, high-school physics texts dwelt painstakingly on simple machines and the principles of refrigeration, and also had a section on sound; chemistry texts devoted considerable attention to various industrial processes; the biology curriculum emphasized taxonomy, nutrition, and disease.

A second theme characteristic of the efforts to change science teaching was that of highlighting the methods employed by scientists, what can be called the spirit of inquiry, in the various science fields. It was intended that the textbook be a guide and that youngsters be encouraged to observe, hypothesize, experiment, and speculate about different conceptions of the subject matter at hand, and occasionally comprehend some of the history of major scientific ideas. Field and laboratory work were designed not solely to confirm the statements in the textbook, but to help youngsters uncover knowledge on their own. In one elementary school science program, for example, the children were challenged to find out how many different ways they could make a mealworm move backwards without touching it with a solid object. In this case (and in a few others), there was not even a textbook to provide the authoritative answer. The aim was less to teach about mealworm behavior than to engage children in the process of scientific discovery.

A third, sometimes more muted aim of many of the new science programs was to emphasize the aesthetic qualities of the subject—for example, by underscoring the ubiquitousness of certain concepts across fields, and preparing youngsters for the joy of accidental discovery of phenomena like randomness, symmetry, equilibrium, periodicity, and adaptation.

Putting aside the question of the appropriateness of the content, even for bright children, such approaches to science teaching, howev-

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er attractive, ask a great deal of the teacher, not least in the amount of subject matter knowledge that is necessary to deal effectively with classroom events that are not entirely predictable. They therefore demand of the teacher a turn of mind ready to accept classroom discussion about topics with which she or he might be only minimally familiar. Such curricula put the teacher at risk. Specific factual learnings often are unstated, and not all teachers feel comfortable if they do not know exactly how the lesson will develop. Further, such relatively unstructured approaches make it difficult for them to describe to children and parents exactly what youngsters are supposed to learn. It is much easier to explain and justify teaching how to classify species than to explain to children and parents that you are trying to help the youngsters draw reasonable inferences from available evidence. Easier, also, to cover the material in a textbook and prepare the youngsters for a factual examination on the classes of levers, or the stages in mitosis, or the system for determining the hardness of rocks and minerals, than to judge the degree to which children are becoming intelligently skeptical about new claims for nuclear safety.

The public image of science is that of a field rich in facts about the natural world. It is understood that schools must select from a vast range of possibilities those that are most suitable for teaching. But conveying authoritative information is the goal easiest for most people to understand and accept. The science today's adults have studied has been of such a nature. Science news on television and in the other media tends to emphasize new discoveries. Therefore when attempts are made to revise the science curriculum to highlight the spirit of scientific inquiry or to limit coverage to a few fields, the lack of familiarity of the new approach is disquieting for almost everyone. It is not insignificant that such curriculum reform efforts are initiated by those who are most familiar with the subject matter, who to some degree take its fundamentals for granted, and who choose to dwell instead on the more human aspects of science and those features that are to them the most challenging and pleasing. But most teachers are not as well informed as the university-based curriculum developers, and the public rarely seems ready for such innovations. Most people want something practical, or at the very least, recognizable.

How have teachers responded to this problem? Most understand the newly articulated goals and may sense their merit, and in order to feel progressive, will want to try the new program, or at least *seem* to try it. During the height of the curriculum reform movement, it was not uncommon for teachers to use the new books, but when their

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authors observed some of the classes, they became alarmed. Rather than employ the investigative spirit that inspired the writing, the teacher often had the children read certain passages aloud, or she or he asked a question that the children could only answer correctly by canvassing their memory or the textbook.

The most common form of teaching in American schools is still the recitation: the teacher asks a question; the child answers it, preferably in the words of the textbook. Typically, the teacher assigns, the children recite, the teacher tests, and then—sometimes—the class participates in a discussion. Furthermore, the questions that teachers ask in science frequently focus on definitions or terminology. What are the three characteristics of the nervous system? What is the difference between a threshold and subthreshold stimulus? What is the difference between the nervous system of the amoeba and the human? The essence of the children's task is to search the text for a sentence that contains the correct answer. In the words of the Stake and Easley team, "The student who tries to improvise an answer reveals, with characteristic hesitation and the broken constructions of ordinary spoken English, that he has failed to work thoroughly on the text, and the response is greeted with disapproval."[7]

Still, it is primarily the teacher who determines what youngsters learn in the school. Those who wish to depart from prevailing practices can do so, particularly if they are good at it. Not everyone relies excessively on the recitation. About 60 percent of high-school seniors report that "student-centered" discussions are used "fairly often" or "frequently"; 45 percent say that project or laboratory work is used often.[8] In a school system as vast and diverse as America's, virtually all types of teaching can be found. The amount of autonomy in the classroom is still considerable, and teachers have the latitude to give disproportionate attention to their favorite topics, as the following examples show.

At the elementary school level, Ms. Pacheco, a fourth-grade teacher, is a rock collector. The children in her class can expect a significant fraction of science time to be devoted to identification and classification. A third-grade teacher, Ms. Schwartz, has had success in incubating chick eggs, and her annual science program consists mostly of developing, examining, and preserving chick embryos. The syllabus for the school district does not as a rule specify the study of rocks at grade four or chick development in grade three, but for these teachers, such instruction is the liveliest feature of the science program; the teacher looks forward to it, and so do the children. After a

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few years, it is known throughout the school what each teacher's interests are, and the children, even if they groan ritualistically, usually look forward to chicks with Schwartz or rocks with Pacheco.

If Schwartz is appointed to a district curriculum committee, she might suggest that all third-graders study chick development, but even if the committee accepts the idea, one can be sure that not all third-grade teachers will wish to incubate chick eggs, and of those who do, most will not have Schwartz's knowledge or flair. Similarly, Schwartz, if told to teach the laws of motion, might choose to ignore the topic or teach it poorly because of lack of knowledge or interest.

Such differences in tastes, motivation, and ability among teachers are evident even at the high-school level. Many high-school teachers have developed a particular specialty in some facet of their subject. They often have learned to handle some topic with particular skill—often with a verve that may or may not characterize their handling of other subjects—and they introduce it when the time seems most propitious.

In search of the archetypal "Mr." (or Ms.) Science, the Stake and Easley group found one—Mr. Armison—in an outlying suburban community in southern California. Here is a description of one of his physiology lessons.

TEACHER: Let's start with deep peroneal nerves. *(Another team of four students, four husky boys, goes to the front tables, facing class)* OK, the problem is deep peroneal nerves. The deep peroneal nerve has been cut; there's function in one leg. What loss of muscular function is expected? Can this person come into your class or office? How would you expect the deformity or problem to be exhibited?

STUDENT 1: OK. He would lose one hundred percent of his dorsal flexion and about eighty or ninety percent of his inversion, so as he came in there, he wouldn't be able to raise his toe. When he walked, he'd come and he'd walk like this. *(Demonstrates down aisle)* He wouldn't be able to raise his toe, so he'd just drag it along. It might also go out a little bit.

TEACHER: What remaining muscles innervated by other nerves can be trained to do some of the lost function?

STUDENT 2: *(Using notes)* Well, first of all, the muscles that are going to be lost when you lose the deep peroneal nerve are the tibialus anterior, the extensor digitorum longus, the peroneus tertius, the extensor hallucis longus, and extensor digitorum brevis. To make up for those muscles which were lost, the tibialis posterior would take over, along with the flexor hallucis longus and the flexor digitorum longus. They would be generated by the posterior tibial . . .

TEACHER: Take over in what respect?

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STUDENT 2: They would bring back the dorsal flexion and the loss of inversion. They would compensate for what is gone but they would bring back, y'know, only ten to fifteen percent of it.

TEACHER: Of the dorsal flexion?

STUDENT 2: Of the inversion.

TEACHER: Oh, OK. How about dorsal flexion? Any of those that could be trained?

STUDENT 2: No.

TEACHER: Good . . . [Next.] Describe therapy exercises in anatomical and in layman terms to strengthen the remaining muscles.

STUDENT 3: OK. There's so much lost that there's nothing you can do for dorsal flexion. As for inversion . . .

(The rest of the class paid attention, laughing at primitive efforts to draw a foot, some hoping that their turn would be put off a day.)

Armison expects not perfection, but hard work, verbal facility, and reflection. He presses the youngsters hard. The children respect him. But even Armison, when he teaches a topic he knows less well, like marine biology, has uninspired lessons.

Stake and Easley report that Armison, like many skillful teachers, does not take kindly to suggestions from others about what he should teach. He believes that science teachers should have their own professional societies to talk about new developments in the field, and he despairs of much assistance from the district, from state authorities, or from the federal government.

> I don't like, nor do I very often use, materials prepared in total units by somebody someplace else. Every course is what one teacher has to make it. It has his personality, his stamp on it. No one else could teach this (anatomy) course. . . . Science rooms are filled with some other teacher's dreams of what a class should be. It just stockpiles back in a corner someplace.

During the last ten years, there have been serious attempts to standardize science programs, those for youngsters of modest academic interest or ability in particular, to bring them to a level of "minimum competency." With the increased use of advanced placement examinations, there has also been a tendency to standardize courses for academically oriented youngsters, to teach the course that best prepares them for the examination, basically the introductory college-level course. Both have the goal of improving the children's scores on externally developed tests. One result, in both types of classes, is to diminish the latitude of the teacher and make it harder for Green, Schwartz, Pacheco, and Armison to do what they like best and are best at. The resulting problem: As momentum develops for more

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uniform testing programs—and therefore courses—is a point reached at which teachers with special ability and interest in science begin to see their scope limited? Further, do those who contemplate a career in science teaching have a picture of the nature of the work that is reasonably consistent with the way the job is evolving?

Despite the fact that educational debate about the purposes of science teaching has not really considered the range of possible purposes—each advocate for a particular approach instead attempting to describe how it advances certain specialized goals—educational aims are nevertheless being stated with increasing precision, with curriculum guides and textbooks often listing "desired outcomes." The trend is toward specificity of content, but there is a lack of clarity, agreement, and understanding about general goals and choices.

Such a development has a twofold effect: it makes it more difficult for teachers to rationalize their favored approaches to the subject; at the same time, it diminishes their opportunities to pursue topics that seem rich in educational potential. Yet up to a certain point, multiple demands and expectations actually provide increased autonomy for the teacher because they allow greater choice.[9] The argument for ambiguity in educational goals is powerful and, for the most part, appealing, but such virtues as ambiguous goals may have are limited when extensive mandated testing programs are introduced. Tests—particularly those that are necessary for advancement to the next level of schooling, or the results of which are made public—rivet the attention of teacher, children, parents, school administrators, and the press as do few other features of the educational program, and the effect is to constrain the teacher. The constraint usually results in more youngsters passing the standardized exam, and this beneficial result is its intent, but it also diminishes flexibility that in the hands of some teachers enhances educational quality.

What if discussions of possible science education policy were broadened to include more explicit consideration of priorities—even to include possibilities that are unlikely, or even unwise, but that serve to underscore the importance of what is omitted when expanded mandatory testing or increased hours in required subjects are chosen? In view of what we know about the nature of science teaching and the preparation of science teachers, what options are profitably highlighted to increase understanding of the nature of the problem and the wisdom of projected policy? Several speculative possibilities are outlined briefly here in that spirit. They are based on two premis-

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es: (1) for the foreseeable future, any reasonable set of strategies for the improvement of precollege science teaching must assume that the teacher is central, and (2) policies should be constructed at least as much to enhance teachers' strengths as to guard against their weaknesses. If external initiatives are directed exclusively toward assuring some prespecified minimum level of effort or achievement, and not toward enhancing the work of those who do the job best, the profession will gradually become less attractive to its most able practitioners, because the minimum tends to become the standard.

A key issue that receives little attention centers on the most effective use of the talented people who do choose teaching as a career. At the moment, they usually are assigned to classrooms in most districts on the basis of the preferences of the most senior faculty or as a result of their personal influence within a given school. It seems as clear as anything ever is in the field of education that the number of qualified teachers will be limited for many years to come, that the need for high-quality science teaching is great, and that difficult choices must be made about how to use a scarce resource. Even when teaching was a more popular career choice than it is today—just a dozen years ago—only about 20 or 25 percent of those who entered the field were able to rank academically with the top half of those in other preprofessional four-year programs. But that group was a significant factor in sustaining education quality in many districts. Now the proportion of able people entering teaching is smaller; perhaps only 10 percent correspond in academic attainment with the top half of students in other programs. How are these people assigned? Are they deployed as effectively as they might be?

Children with strong intellectual interests are taught with great difficulty by poorly informed teachers, particularly during the secondary school years. A policy that tends to be followed—but one that might well be pursued more consistently—is to assign only able science teachers to work with youngsters of highest achievement in the high school. (This is not to suggest, of course, that these teachers should not work with students of lesser ability, too.)

In addition, and perhaps more controversial, school districts should give serious attention to offering science courses only to the degree that qualified teachers are available. Even if "qualified" were defined broadly to include all those teachers certified in the subject, there would be a significant winnowing out of teachers who have been redirected to science from English or social studies or physical education because of declining enrollments. If such a policy were

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pursued, a certain amount of science now taught would disappear from the schools, temporarily one would hope, but the loss probably would not be great. Nothing kills interest and misrepresents the field as surely as an unprepared teacher.

Another approach that is seldom considered, but one that is nevertheless worthy of attention, is to expand the influence of the most effective science teachers by enabling them to reach larger numbers of youngsters. At the university level, it is common practice for professors to lecture to large sections and for assistants to supervise laboratories and discussion groups. Maybe it should be the other way around, but it might be useful and instructive to experiment with this system in the high schools, by departing from the conventional class size of about twenty-five students. In this way, more students would experience the intellectual stimulation of being taught by gifted teachers who bring both skill and flair to their subjects.

Another possibility: In view of the scarcity of strong new science teachers, perhaps a standardized science program that follows a specified text in all subjects should not be a requirement for all students beyond the teaching of some fundamental principles. The "core" would take only a portion of the school year. The remaining part of the science program in high school, as in most elementary schools, would be based in large measure on the qualifications and interests of the available teachers. In the elementary school, computation and especially reading are subjects to which every teacher devotes major attention. Beyond these basic subjects, the teacher is relatively free, especially in science, to choose the topics. If such a pattern were followed at the secondary school level, some teachers would no doubt use available texts, but others would pursue their special interests in thermodynamics or the history of astronomy or current views about plate tectonics, and the science that is taught would probably be more accurate and vital, and would more likely lead to further study by the students. In the minds of the students, the curriculum may seem at least as sensible and coherent as a program taught ritualistically by a teacher with little information about the subject or interest in it.

Still another possibility would be to concentrate science teaching resources to a much greater degree than is done at present at the elementary school level. Able youngsters seem to be able to progress to college even with uninspired teaching, provided their motivation is sustained when they are young. By focusing more of the available science teaching talent on elementary schoolchildren, science interest

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would be heightened among a broader group of the population than is now the case, and those who do not choose to move into science-related careers would have a general background sufficient to raise science knowledge in the population significantly. In the 1950s it was not uncommon to have science teachers in kindergarten through grade-six classrooms, sometimes teaching special classes, sometimes working on science lessons with the regular teacher. Such specialists have been eliminated in most districts that employed them, not because they were unsuccessful, but because budgets became tight.

None of these possibilities have been studied sufficiently to be advanced without reservation. Each has some superficial appeal; each some serious flaws and costs. They are offered, rather, to illuminate potential opportunities that are seldom considered but that are useful in sorting out priorities in a climate of severe economic constraint. Perhaps the country will become more alarmed, and consequently more serious, about improving science teaching—even to the point of significant infusions of new money for science teachers' salaries or for the education of those in or entering the field. But regardless of the financial outlook, sensible deployment of the teachers available, and serious attention to how they use their time, are topics that deserve much more attention than they have received.

Education, perhaps more than any other social policy sphere, is responsive to public concerns and demands. There are close to 20,000 school boards around the country monitoring teacher and student activity in the various districts, and not only are state legislatures becoming more assertive, but the popular press continues to find public education a compelling subject. Teachers and school administrators are scrutinized carefully, and the pressures to try to respond to public concerns are irresistible.

Furthermore—and fortunately—the system is diverse. While it is possible to outline overall national trends over a period of a decade or two, the process by which schools improve or decline consists of tens of thousands of individual decisions, inside and outside a given classroom, about funding, curriculum, teacher education, and physical facilities. Each state legislature is hard at work on the very same issues that absorb every other state legislature. Every district in the country addresses issues faced by every other district. In such a climate, it is inevitable that different choices will be made. Here and there, special pay scales for science teachers will be introduced. Here and there, the local university will develop a cooperative program

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with nearby schools to examine curriculum on a regular basis. Here and there, computers will be used to teach a fraction of the science course. Here and there, plans will be instituted to group youngsters in a fashion that maximizes their contact with gifted teachers. Some decisions are wise. Some are silly. Some produce results exactly counter to those intended. (Minimum competency tests have a downward leveling effect because they redirect teacher time from youngsters who do well in school to those who don't. Of course, they level upward, too.)

However uncoordinated such a pluralistic approach may seem during periods of perceived crisis, it may well be that the soundest policies are formulated when people with immediate responsibilities for improving the education system are accorded some scope, provided they are striving for aims that are supported in the community, at least implicitly, and provided they are able to consider a suitably broad range of options, even some of those suggested in this essay. Government agencies can provide incentives and attempt to fill important resource gaps; but while problems are general and at some broad level can receive constructive attention, solutions are almost always local and special. A high school with Armison—Stake and Easley's archetypal "Mr. Science"—as science department head does well to respond differently to the challenge of improving science teaching than one with Parker—who was *not* trained in science—as its head. In some districts, it may make sense to emphasize elementary school science at the expense of the high school, but in other districts not.

It is this balance between identification of general goals to which most people can subscribe and the preservation of local capability to develop sensible methods to achieve those goals that represents the ideal in education reform. To become too prescriptive is to risk transforming teaching into an occupation that will attract few people of high ability. To become too anarchic is to risk the development of educational programs that do not elicit sufficient support—and therefore resources—for high-quality education to occur. But whatever policies are adopted for the improvement of science teaching, the closest attention should be given to their probable effect on recruitment and retention of the nation's most capable people as teachers. At the moment, nothing in the school or in the education policy arena is more important.

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ENDNOTES

[1]Robert E. Stake and Jack A. Easley, Jr., *Case Studies In Science Education* (Urbana, Illinois: Center for Instructional Research and Curriculum Evaluation, College of Education, University of Illinois, 1978).

[2]It would be well to question the widely held assumption that the best course for those with science aptitude and ability is advanced placement. College-bound students will take the courses later, in any event. Perhaps the high-school years should be used for broader intellectual exploration rather than anticipatory college-level specialization. A less examination-driven opportunity to study some topics of special interest in depth might be a better use of high-school time for student and teacher. In small schools, particularly those in rural areas, advanced placement courses are not offered, but it would be misleading to infer that some of the science teaching is not of high quality.

[3]National Assessment of Educational Progress, *Three Assessments of Science, 1969-1977: Technical Summary* (Washington, D.C.: National Center for Education Statistics, 1979).

[4]An argument has been advanced recently by Mortimer J. Adler and his colleagues that schooling should have the same purposes for all people, and that every student should have the same curriculum, except for the choice of a second language. See Adler, *The Paideia Proposal: An Educational Manifesto* (New York: Macmillan, 1982).

[5]These stories are cited in Orra E. Underhill, *Origins and Development of Elementary School Science* (Chicago: Scott, Foresman, 1941) and are drawn from such children's books as *Alfred, or the Youthful Inquirer* (1824), *Peter Parley's Farewell* (1841), and *The Alchemist* (1818).

[6]Elizabeth Mayo, *Lessons on Objects: As Given to Children between the Ages of Six and Eight* (San Francisco: A. Roman, 1876).

[7]Stake and Easley, *Case Studies in Science Education,* p. 19:6.

[8]National Center for Education Statistics, *The Condition of Education* (Washington, D.C.: Government Printing Office, 1982).

[9]Lee S. Shulman, "Autonomy and Obligation: The Remote Control of Teaching" in *Handbook on Teaching and Policy,* edited by Lee S. Shulman and Gary Sykes (New York: Longmans, in press).

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Barton Childs and Faith Hickman

Human Genetics: One Approach to Scientific Literacy

AMERICA'S SCHOOLS, like institutions everywhere, are slow to change, but they do respond eventually to the strong currents of new direction in the society. The accelerating accumulation of scientific knowledge, along with the technology growing out of it, is one such current, and there is growing evidence that policymakers as well as science educators are keenly aware of this force and of the need to provide educational experiences that will help our young people deal competently with its effects.[1] The job will be a difficult one, because it goes beyond simply presenting the facts and methods of science to include ways of thinking about how science impinges on social values and ethics and how to use new scientific knowledge in making decisions that pertain to daily living.

Because of a growing concern that science education should try to meet the personal, social, and career needs of students, the National Science Foundation provided support for a group of experts, in an undertaking called Project Synthesis, to review and interpret a large volume of data—gathered in the 1970s by NSF and the National Assessment of Educational Progress—on the practices and trends in education in the natural and the social sciences, and from there, to synthesize a new approach to science education.[2] Project Synthesis had two goals: to report on past and present experience, and to analyze trends that could be helpful in charting a future course for science education. The experts concluded that present curricula are organized around the structure of each discipline, with only marginal emphasis being given to social problems or personal applications of knowledge. Present-day classroom practice, they found, involves mainly the discovery of a single "correct" answer in laboratory exer-

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cises and the presentation of facts in a value-free context in lectures and discussion. In contrast, the panel members predicted that the life science curricula of the future will be organized around the theme of human adaptation in both the scientific and social senses, and that the use of biological knowledge in making decisions will be an important goal of programs dealing with the biological aspects of social problems from the perspectives of values and ethics.

The realization of these predictions will require a good deal of experimentation. There are at least several equally valid interpretations of such goals and a large number of worthwhile proposals for achieving them. For example, the Project Synthesis team made similar recommendations for both the physical and life sciences, but the programs that seek to achieve these recommendations will most likely vary significantly in the topics addressed, the ages of the students, the content and form of instructional experiences, and the behavior of teachers and students alike.

In the life sciences, these goals may more likely be achieved if human biology were given much greater prominence than is customary.[3] Students are interested in themselves, their origins, and those qualities that make each of us unique. Genetics lies at the heart of human biology no less than at that of all organisms. It is a subject that is at present much in the scientific and public eye, and the application to human problems of knowledge derived from the laboratories of molecular and cell biologists is already having an impact on mores and ethics. Since many of the questions raised impinge on values and morals, they are germane to social studies and health education as well as to biology. An approach to one kind of scientific literacy, therefore, might be through the study of human genetics. Our purpose in this paper is to consider how this might be done.

Three questions come to mind: Why should genetics be given a central place in teaching biology? To whom should the teaching be directed, and when should the subject be presented? How and in what form should it be offered?

WHY TEACH GENETICS?

A subsidiary but related question to those above is one of content, for we cannot say why an interest in genetics should be promoted without making plain what compels us to study it.

The tradition in high-school biology is to deal mainly with Mendelian genetics using *Drosophila* (the fruit fly) and plants as models.

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Human traits are also included, usually sickle cell trait, hemophilia, and PTC tasting. Often, other less clear traits, such as mid-digital hair, type of ear lobe, eye color, and the like, are also cited as if they were Mendelian characters. Further, newer texts deal matter-of-factly with DNA and chromosome structure, as well as with cellular anatomy and function, and a few cite such inborn errors of metabolism as phenylketonuria. All of this is instructive and illuminates genetic principles admirably—but what does the student do with the information? Usually he or she remembers it until exam time and then forgets it. Such knowledge would undoubtedly be useful if the student were later on to find himself or herself in some medical-genetic crisis, but medical geneticists and genetic counselors agree that high-school and college graduates who have studied biology rarely remember the principles of genetics when faced with making reproductive decisions.[4]

These deficiencies have been observed by perceptive high-school teachers who question the value of knowledge that students do not recognize as related to their own lives. They believe that the mission-oriented aim of enhancing awareness of problems to be faced later in life can be achieved even while pursuing the discipline-oriented goal of intellectual development.[5] Accordingly, biology teachers have demonstrated an interest in three areas of genetic knowledge: (1) the genetic relationships of human beings to one another and to other living organisms; (2) genetics in the context of health and disease; and (3) the impact of modern knowledge of genetics on ethics, values, and social relations.

Genetic Relationships

Modern technology has released human beings from constraints that once seemed immutable, and the pace of change will continue to accelerate. In the face of such rapid transformations, it could be a stabilizing experience for students to discover what limits have been set in the course of eons of evolution, to discover that there is an order in the biological kingdom, and to consider what accounts for it. The fundamental data required for the intelligent discussion of such issues are available: all living organisms share the same DNA, differing only in the number and arrangement of nucleotides, and all higher organisms share mechanisms for translating genetic information into homeostatic control and development, and for variation and evolution.

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The elaboration of such facts might form the basis for the genetics section of any biology course. But the fun of learning genetics should derive from thinking about the implications of such information for similarities and differences both within and between the species, and for evolutionary change and adaptation. Can genetics explain the simultaneous existence of so diverse an array of species? And what accounts for the varieties of sizes and shapes, competences and deficiencies, of the individual members of the species?

Interspecific Relationships—Although man dominates the earth, the presence of strong genetic relationships between the species suggests that we are all inescapably subject to the same biological rules. For example, in a comparison of amino acid sequences of proteins in many different organisms, it has been found that there are very few differences in histones, no matter how divergent the species. For cytochrome c, a protein of 110 amino acids, the difference between man and *Macacus mulatta* is only one amino acid, and between man and the pigeon, 16. Further, an organism so dissimilar from man as yeast shares half its amino acids. The hemoglobin β chain has 147 amino acids, and when human and chimpanzee β chains are compared, there is a difference of only 1 amino acid, while the β chains of human beings and gorillas differ by only 4.[6] This similarity in amino acid sequence means two things: first, living organisms seem to share the same metabolic machinery, designed—presumably as a result of adaptation—to be appropriate for the purposes of each; and second, genetic distances, or evolutionary relationships between species, can be measured in terms of differences in amino acid sequences.[7] Obviously, the variation in amino acids is a reflection of differences in DNA sequences, from which we infer that the diversity of the forms of life is the result not of extreme variety in DNA sequences, but of the many combinations of genes, each one of which bears similarities to homologous alleles present in other species. The strong genetic kinship of all life means that although we are culturally sharply divergent from other beings, we are subject to the same limiting forces, and that, while adaptation to the conditions of its surroundings may make each species independent in some ways, no species can free itself entirely of its dependence on others. We may tire of being reminded of these biological restraints, but we defy them at our peril. It may be that a visceral grasp of the extent of this genetic kinship would promote a more biocentric viewpoint to replace the rigid anthropocentrism that has pervaded human culture from antiquity.

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Differences within the Species—Intraspecies variation is simply an extension to individuals of the genetic qualities that differentiate the species. Selection has fixed in the gene pool certain alleles of tested quality that are species specific; that is, genes that determine proteins with amino acid sequences that identify them as human or avian or bacterial. When we compare to its human version the amino acid sequence of an enzyme from a whale, the differences are such as to make the identity of each unmistakable. And if the comparison were extended to many proteins, we could construct lists of genetic differences that in the aggregate would define "whaleness" or "humanness," or at least would define limits within which whales or human beings *could* vary. The limits within which they *do* vary—intraspecies variation—are set mainly by the extent of variation of the species-specific genes, by the combinations of alleles, and by the varieties of individual experiences. It may be that the last of these is of greater significance in the human species than in any other, both because human culture is so complex and so varied and because human development is so prolonged. The relatively great duration of human juvenility provides more opportunity for variation in the outcomes of the interactions of gene impulse and experience. But if this makes man more variable than other species, it is in amount rather than in kind.

Thus some knowledge of genetics, even if only a little, is necessary for an understanding of human individuality—including oneself—of the identity of man as a species, of our place among living organisms, and of the mutual dependency of all forms of life.

Human Health and Disease

The genes specify the macromolecules that determine the structure, organization, development, and function of the cells, the organs, and the organ systems of the human body. In doing so, they set limits to the capacity to respond to conditions of living. They are the architects and governors of homeostasis, and since mutations and recombination are the sources of variation and individuality, each of us must have our own ways of responding to our experiences—of making the best of some, defending against others, or succumbing to conditions that exceed homeostatic tolerance. The last is called disease, and it is simply a result of a bad fit between an individual's competence to maintain a steady state and the forces that oppose it. And this misfit is an individual matter; experiences that are catastrophic for some are of little moment to others. Obviously, some

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mutants have effects that represent a bad fit with any experience ordinarily encountered in life, and the diseases they cause are usually called monogenic or, more simply, "genetic" disorders.

It is the triumph of medical genetics that hundreds, even thousands, of genetic disorders have been recognized and described, and owing to the predictive nature of Mendelian transmission, counselors are able to give stricken families rather precise advice about reproductive odds and choices.[8] Furthermore, heterozygote detection and the discovery of other kinds of genetic risk factors have increased the choices available to parents, who, possessing appropriate information, may wish to go ahead to take a known chance, or to avoid it altogether. In weighing probabilities, some knowledge of the nature of genes and how they are transmitted is obviously required to inform the decision.

Although these "genetic" diseases are very numerous, each is infrequent, varying from one in ten thousand to one in a million. In the aggregate, they probably afflict no more than a few percent of the population. But the medical literature is beginning to reflect the accumulation of evidence favoring the genetic contribution to diseases that have usually been called "environmental": high blood pressure, heart attacks, stomach and duodenal ulcers, cancer, psychotic behaviors, and other, mainly chronic illnesses that we see, with disturbing frequency, in the second half of life. These are diseases of prolonged morbidity, and although treatment often averts death, the patient is not always "cured." The idea of preventing these diseases is becoming increasingly attractive, and prescriptions and proscriptions are finding their way more and more into the medical literature and the public press. It is suggested that if we take certain dietary precautions and change our life-styles, we can prolong life and enhance its quality.[9] Certainly we should take these recommendations seriously, for if followed, they may prolong life and reduce morbidity. By omitting to specify that not everyone is equally susceptible to each disease, however, the recommendations risk prescribing privation to some for whom it is unnecessary, and an insufficiently rigorous regimen to others who may be most in need. We are at the beginning stages of the sorting out of those who have genetic risk factors from those who do not; but if knowledge of the genetic component of the common chronic adult diseases accumulates as rapidly as that of the infrequent genetic disorders of infancy and childhood, we are certain to make great strides in the diagnosis, treatment, and prevention of these illnesses—perhaps especially prevention. The genes associated

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with the "genetic" diseases of infancy are broadly incongruent, often leading to developmental distortions and death under nearly all conceivable conditions, and offer only limited opportunities for conventional forms of prevention. In contrast, the genes associated with the common chronic disorders of adult life produce effects that are bad only under certain circumstances, which, if known, might be adjusted, avoided, or substituted for, with the intention of blocking, diverting, or blunting their disadaptive effects. So it is here that opportunities for the prevention of morbidity in specific individuals will present themselves most pointedly. And the success of such preventive measures will depend largely on the wholehearted collaboration of those at risk. They must be informed not only of the nature of the disease they are at pains to avert, but of the genes involved and the kinds of experiences likely to bring out their disadaptive influences.

It is of course true that the adverse effects of a number of monogenic diseases—phenylketonuria being the best example—can in some cases be averted also. But prevention of most of these diseases will most likely take the entirely novel form of preventing the birth of affected fetuses. This paradoxical behavior clearly does violence to conventional mores, both medical and general, and it has provoked heated controversy. But this approach is only one among many applications of those penetrating insights into the nature and action of genes that constitute the "new genetics," and that raise sometimes polarizing social and ethical issues.

The Social Impact of Genetics

It is entirely possible to bypass public opinion and leave medical genetics to the physicians, and the determination of ecological issues to politicians, conservationists, and industry. But in a democratic society, the people must know the facts that bear on the issues affecting their lives. In these times, however, those facts are often comprehensible only in a context of preexisting knowledge. There are at present a number of issues of great social impact about which polarizing views are stridently, even violently expressed and reported by the press, and which can be understood by the public only with the help of some knowledge of genetics. Among the most prominent of these are antenatal diagnosis and abortion, "Creation Science" versus evolution, hereditarian views of human behavior, and social responsibilities to the handicapped.

Antenatal diagnosis—Diagnosis of more than one hundred diseases[10] can now be made in utero, giving parents the option—usually

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exercised—of terminating the pregnancy to prevent the birth of an affected baby. This capability is a result of the rapid expansion of knowledge of diseases caused by chromosome abnormality or mutant genes. The number of diseases that can be diagnosed in utero will continue to rise, taking a sharp turn upward as new genes are discovered in human chromosomes.[11] It is anticipated that not only will many more genetic disorders be given the biochemical definition required for reliable antenatal diagnosis, but that the rapid elaboration of the human gene map will make available numerous genetic markers that, when shown to be linked to genes associated with particular disease, can act as trustworthy diagnostic signposts. Some important questions will inevitably arise: Can this form of prevention achieve widespread acceptance by a public that until only a few years ago considered abortion for any cause other than maternal danger as both illegal and immoral? Given the extent of individual variation in the onset, severity, and duration of diseases caused or conditioned by mutant genes, which diseases are suitable for antenatal diagnosis, and which individual fetuses should be aborted? Current opinion suggests that despite some determined opposition, the majority of the public will in time accept abortion to prevent the birth of fetuses with genetic diseases. For the second question, there must always be a zone of uncertainty in which answers will depend upon the attitudes, values, and customs of the societies and individuals concerned. That some knowledge of genetics should be brought to bear on all decisions regarding these issues—whether the decision is one of broad social acceptance of the procedure or its rejection, or whether it is that of an individual couple to have the procedure or not to consider it at all—hardly needs saying.

The most vociferous opponents of antenatal diagnosis and abortion as a means of prevention take a dogmatic view and are uninterested in the facts, either genetic or social. Nor, paradoxically, are they concerned with the lives of the deformed or sick fetuses that they are so determined other people should bear. But for those who must face the physical, emotional, and financial drain that a seriously disabled child brings, the knowledge needed to exercise this option offers deliverance. One beneficial effect of antenatal diagnosis has been an increase in the delivery of normal babies, infants who would never have existed in the absence of this option, because without it, potential parents would have aborted undiagnosed fetuses or would have forgone pregnancy altogether.[12]

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"Creation Science" versus Evolution—Given its prominence in American folklore, one might suppose that the furor aroused by the Scopes trial would have settled once for all the obligation of the schools to teach evolution as a valid idea, supported as it is—and was even then—by contributions from so many biological disciplines. But far from promoting it in high-school curricula, the trial caused some publishers to run for cover.[13] The word "evolution" disappeared from the index of many textbooks, and the idea itself was treated with elaborate circumspection in the text. It was not until the appearance of the Biological Sciences Curriculum Study textbooks in the early 1960s that evolution was given unabashed and forthright treatment in high-school biology. Since that time, molecular biologists and biochemists have illuminated the well-established views of paleontologists and anthropologists by revealing, through biochemical comparisons, the validity of relationships based originally on morphology.

But evidence alone is apparently not enough. To the coalition of religious fundamentalists and others, science represents a threat to both religious and moral values and to family discipline. Science teaching in school, most particularly reproductive biology and evolution, has given them a point of departure to make known their concern and unrest. They have advanced the idea of "creation science" as an alternative to evolution, and seek to have it taught in science courses so that children can make up their own minds. But in a recent decision in Arkansas, the court held that "creation science" is not science at all, but religion, and therefore in conflict with separation of church and state.[14] Creationists beliefs are based on dogma, not science, and thus are not open to instruction. But when state legislatures and school boards and their constituents are asked to make decisions about what biology to teach their children, their decisions should be based on some knowledge of what science is, and of the genetic elements that make evolution possible. It is therefore more important than ever that the public, who in the end set standards for their children's education—and therefore for society—be informed.

Hereditarian Views of Behavior—The discovery in a Scottish prison of an excess of tall males with a surplus Y chromosome was thought by some to suggest that having two Y chromosomes would lead inevitably to behavior that must put the individual possessing them on the wrong side of the law. Some even questioned whether an

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XYY karyotype, like insanity, might not excuse violent and antisocial behavior, and the less responsible press, in defiance of the plain fact of its wide distribution in a generally peaceable population, referred to the Y as the "violence chromosome." This misunderstanding is of itself good reason to promote the study of science and its method, since the apparent strength of the association between the XYY karyotype and criminal behavior was owing to a bias of ascertainment. It has been shown that one out of a thousand newborn males have the XYY genotype and that although some have mild mental retardation or learning disabilities, and some are behaviorally unstable, others are not; certainly, most are law-abiding citizens.[15] It is simply that distributions of measures of height, cognitive scores, and behavioral properties of XYY males do not quite overlap those of normal XY males, but are skewed a little in the direction of abnormal scores.

There were other controversies. It was said by some that the XYY genotype was completely innocuous and that the investigators who sought to discover its fequency by testing consecutive newborn babies, and who then followed the development of infants with this as well as with other sex chromosome abnormalities, would certainly prejudice the normal development of these infants by telling the parents that their baby had an abnormal karyotype. It was said, too, that the studies were an invasion of the privacy and rights of the subjects and their families.[16] Enough heat was generated to terminate at least one such study. We know now that infants with any of the several sex chromosome anomalies, including XYY, *are* at risk for developmental problems.[17] Some seem unscathed, while others may be retarded in various ways and in various degrees. What was lost to view in the public controversy was that the extra Y chromosome simply creates a state of potential, or of susceptibility, in an individual that can be overcome, perhaps by his other genetic qualities or by the climate for development in the family and surroundings.

Another controversy arose over the so-called genetics of intelligence, one side attributing almost all of the variation in IQ to the genes, the other almost none.[18] The latter feared—legitimately—that if hereditarian views prevailed, policy decisions based on such claims might seriously affect how educational and other kinds of opportunity were apportioned. Not only could people be stratified according to this putative biological endowment, but society could be absolved of responsibilities to its citizens; if a person failed, after all, it was his or her own fault. The controversy has died down, perhaps because

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the means are not at hand to study the question.[19] Although it seems reasonable to suppose that the genes contribute to variation in IQ scores, there is no way at present to detect them or to find out how many there are, what they are doing, or how their effects are enhanced, diminished, blunted, diverted, suppressed or otherwise affected by the diverse experiences a child undergoes during the long period of developmental flexibility. To someone who knows little of genetics or of development, or who holds the outmoded view that heredity is more important than environment, or vice versa, such a controversy can only be confusing. But some idea of the nature of the genetic material and its control over cellular processes, of its variability and the mechanisms of its transmission in reproduction, must at least suggest the extreme complexity of such a phenotype as IQ; must suggest further that its variability, except when it is very low, is certainly a result of an inextricable tangle of genetic effects working through countless unknown and unmeasured experiences. In this case, what we know is that we do not know enough, and the only sensible action is to put aside the impossible task of unraveling what we do not comprehend and instead offer the best possible opportunity to all without regard to differences in genotype.

The Handicapped—People with handicaps often carry a double burden: their disability may seriously limit their accomplishment of ordinary functions, and they may face rejection by others if their appearance or behavior is more than a little eccentric. Marked discrepancies make most of us uncomfortable; we are often uneasy, anxious, even fearful in the presence of severely handicapped people. S.A. Richardson has suggested that observation of our surroundings leads us to develop expectations as to looks and behavior, and we shy away from those who violate our expectations.[20] This revulsion is reflected in attitudes of self-diminishment, incompetence, frustration, and anger in the handicapped, who, because of a deficiency in one kind of function, may be denied the opportunity to develop others.[21] But some grasp of genetics, even a rudimentary knowledge of gene mutation and of how the genes contribute to variability, can provide a basis for an understanding of diversity, possibly even a tolerance for it, and perhaps a more ready social acceptance of the handicapped. Such insights make clear that the malformed, disabled, and handicapped are simply outliers in frequency distributions. A glance at a distribution of IQ scores reveals no natural and categorical division into normal and mentally retarded. Neither is there any

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point in a distribution of heights that marks a difference between dwarfism and normal height, or that marks the tallest height that can be called short stature, or the shortest height that can be called tall stature. The distributions are continuous, proceeding from the most to the least, and abnormality is something that is defined by custom and how an individual responds to the various demands of his life. But the abnormals are no less a part of the distribution than the rest. They are not categorically different, but represent variants, people whose endowments and experiences place them at some distance from the mean. No doubt many factors enter into attitudes toward the handicapped and their acceptance and treatment by society, but some understanding of their position in the human spectrum and how they came to be there seems a prerequisite for rational and humane solutions to their problems.

WHO SHOULD BE TAUGHT GENETICS, AND WHEN?

Who

Scientific progress is always so far in advance of public awareness that nearly everyone is in some degree ignorant and in need of education. Never before was the notion that education is something we obtain in school to last a lifetime so illusory. Who should be taught, then? Everyone.

Since adults are most directly involved with genetic issues, whether in relation to health, reproductive decisions or social impact, they are a likely target, and we find that efforts are being made in that direction. Very large population-testing for the genes for Tay-Sachs disease, sickle cell disease, and thalassemia has exposed at least three ethnic groups to some basic lessons in gene action and transmission. At the level where most adults learn about advances in science, amniocentesis has had a good press (it was the subject of several "Doonesbury" comic strips) and is mentioned frequently on television programs and in "women's" magazines—all in ways calculated to achieve maximum attention in the struggle to influence legislative votes in the abortion dispute. Several books on human and medical genetics have appeared, including some with such hortatory titles as *Know Your Genes, Your Genes and Your Destiny,* and *The Genetic Connection.*[22] These books exhort the reader to learn genetics for reasons of health—one's own and the health of one's descendants. Other titles are apocalyptic; *Fabricated Man, The New Genetics and*

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the Future of Man, Genetic Fix, and *Genetic Prophecy: Beyond the Double Helix.*[23] All of these and others draw the reader's attention to the ways a knowledge of genetics can be used to improve man's lot as well as threaten established values.

A year or so ago, a series of articles in the *New York Times* told of how companies in various industries are screening workers for genetic traits.[24] It was not clear why these tests were being done; in fact, the author of the articles showed how they might be used more in the interest of the company than in that of the employee. In addition, we have seen that the press drew attention to the XYY issue, and no one can say that gene technology and "genetic engineering" have not had their day in the public eye, whether in relation to possible hazards (which turned out to be less fearsome than was at first anticipated) or in connection with their industrial potential. Nothing focuses attention so acutely, it seems, as the prospect of making money. Since the beneficiaries of these books and magazine and newspaper articles are the better-educated segment of the public, these forms of education are probably limited to those who read regularly. This limitation has been demonstrated; it is the well educated who take advantage of genetic screening and amniocentesis.[25]

The passage of the National Genetic Diseases Act (PL 94-278), awarding money to the states to enhance services for genetic diseases, seemed to promise much for public education about genetics, because such education was provided for in the bill. Indeed, progress was made; a national clearinghouse for information about genetics was set up, financing for curriculum development for children was provided, and some of the state projects supported high-school and junior high-school education as well as genetic counseling for patients and their families. All of these efforts, of course, have been seriously crippled by recent federal cutbacks.

Genetics has always figured largely in college biology, now more than ever, and with advances in molecular biology of mammalian cells progressing at breathtaking speed, it has become possible to make human genetics the principal focus of courses in biology and genetics. Courses are also appearing regularly in the catalogues of community colleges and those of other agencies involved with adult continuing education.

Thus, although no one seems to have assessed the extent and detail of all this effort in education of one kind or another, that fraction of the adult population who read, and particularly those interested in biology, ecology, population problems, and the like, clearly have

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available to them a good deal of information about genetics in general, and human genetics in particular, and about how all this new knowledge is likely to affect people in the future. They add up, however, to only a very small percentage of the adult population, and mechanisms for promoting education for this age group, whether in formal courses aimed at degrees or in continuing education, or informally in television, magazines and the press, cannot reach more than the small number who would be most receptive. What is left to the media is at best unrepresentative of the whole field of genetics (they seldom provide background information) and at worst is distorted in the interest of the merely sensational. It is therefore likely that anything that is best presented systematically and that must reach the bulk of the population must be offered in the course of primary and secondary education. The 80 percent of high-school students who until recently studied biology has dropped to nearly 50. Can it be raised by some reorientation of the teaching of this subject to show students that biology and genetics are in part a study of themselves?

There is plenty of evidence that in secondary education, at least, there is a highly receptive constituency. Modern high-school biology texts emphasize the central importance of genetics to all aspects of life, and some make a point of including a few examples drawn from human genetics. A few make some effort to show how genetics impinges on everyday life, so that students will understand that the processes of life and evolution have meaning not only for health and reproduction, but also for social well-being.[26] That students are ready for such a change, even eager for it, has been demonstrated in both regional and national studies,[27] and evidence of teacher interest is also impressive.[28] It seems that the time is right to shift from teaching biology and genetics as disciplines to teaching these subjects with an emphasis on what they mean in daily life.

Where and When

If we assume that this shift is possible and desirable, how can it be effected? Where in the school curriculum should it appear, and when? To answer these questions, two others must be examined: Is the curriculum already too crowded? Are the students, especially young children, up to it?

The crowded curriculum may be less of a problem than it seems. It may be that human genetics can achieve some of the traditional goals of high-school biology better than the usual treatment can, and in so doing, offer a way of achieving some new goals that science educa-

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tors wish to promote. Although few teachers disagree openly with the recommendations of Project Synthesis that science instruction address social, ethical, and moral issues, equally few have managed to provide this emphasis in their day-to-day teaching. But taking the focus away from pea plants and fruit flies and directing it toward human beings provides natural avenues for the introduction of information and ideas that transcend the traditional boundaries of biology as a discipline. Thus, it is not more time that is needed, because modular materials with a human orientation can, in the same amount of class time, fulfill the requirement of local or state curriculum guides just as well as, and perhaps even better than, the usual textbook approaches. What is required, instead, is the willingness of school personnel to tackle problems that require the synthesis of knowledge from all the sciences, the social and behavioral as well as the natural.

Health education courses are also a primary target. The idea of individual susceptibility to disease based on genetic variability is gradually taking hold, with profound implications for preventive medicine and the maintenance of one's own health. Courses in health education, now provided in most public schools, lack much theoretical foundation, and this void can be partially filled by genetics.

And it would be truly revolutionary if genetics were to be introduced in courses of social sciences, in whatever course man's relationships—whether to other human beings or to nature—arise. Here again, judicious substitution of modular materials can overcome the complaint of overloading.

Genetics for primary and intermediate schoolchildren is another matter entirely. It is unlikely that most children before the ages of fourteen or fifteen can grasp the abstractions of genetics. Although most young people begin to think abstractly by ninth or tenth grade, children in the lower grades think mainly concretely, and would be baffled by probability and modes of inheritance. But the ideas of difference and likeness, uniformity and variability, and continuity and discontinuity, should be within their range.

WHAT TO TEACH

Curricular programs designed by the Biological Sciences Curriculum Study for kindergarten through sixth grade, junior high/middle school, and high school were tried out recently as prototypes. Like several other programs designed by schools, genetic services units,

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voluntary agencies, and individuals across the country, these instructional materials present genetics as a science of fundamental importance to students, both in terms of their personal decision-making and their participation in the formulation of social and public policy.[29]

Elementary School—The elementary school project "You, Me, and Others" emphasizes variety, change, and continuity, concepts that are logical precursors to a student's later experience with formal topics in genetics and with such social issues as family planning and health. The materials present variability, growth and development, and inheritance in relation to the student's own physical and social environment. The program is designed to be integrated into the curricular areas that typically occupy the student's day—reading, languages, mathematics, social studies, and the arts—rather than as a separate course in science or health, and is flexible enough so that teachers can select activities that introduce and reinforce basic scientific principles and modes of investigation.

In the activities provided, kindergarten and first-grade children sort items into categories of living and nonliving, compare physical differences and similarities among members of the class, observe improvement of skills with practice (as an illustration of the measurable properties of some kinds of change), and predict physical and social changes likely to occur in the future. To develop the notion of continuity, students observe the growth and development of seeds, sort organisms of various species into family groups, and identify physical resemblances between parents and their offspring in human and nonhuman families.

In grades two through four, students extend their grasp of the theme of variety through comparisons of body measurements and of individual preferences for foods, colors, and hobbies. The study of change looks outward at the patterns of daily activity, in terms of the probable accuracy of predictions about certain days or certain times of day in the student's routine, and inward at an investigation of changes in heart rate before, during, and after exercise. In exploring the principle of continuity, students in the middle grades study families of human beings and other organisms and construct family trees.

Fifth-graders and sixth-graders begin to study populations by considering their own class as a prototype. Characteristics are measured and evaluated for their usefulness as predictors of the physical, social, academic, and environmental traits of another population, in this

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case, a class in another school. They conduct scientific experiments with preschoolers to see how very young children think about problems. Students also estimate the degree to which an individual's physical and behavioral characteristics are likely to change for biological or cultural reasons. The work on the concept of continuity concludes with a simple introduction to the transmission of specific traits from generation to generation. Games and stories encourage students to explore the implications of inherited disorders for the health status of individuals and their families.

Junior High/Middle School—In designing the program for early adolescents, "Genes and Surroundings," attention was given to the emotional and intellectual needs of learners of this age. The activities cover a wide range to accommodate the differences in background, knowledge, and social maturity in individuals in the many and diverse communities and regions of the country. The program is based on five themes; individuality, continuity, variability in time, variability in relation to others, and adaptation. These are treated as logical extensions of the ideas developed for children in the elementary schools and lead up to the more formal instruction in genetics at high school and later levels.

Themes of diversity and variability remain as strong as in the elementary school program, but here expand to consider the uniqueness of the individual, an especially important developmental concept for the adolescent, whose greatest concerns often seem to be self-identity and self-esteem. Variability among individuals and across time also commands attention. Continuity is again emphasized, but in greater complexity, to lay a foundation for understanding the rules of inheritance that will come with the more advanced study of genetics. Adaptation, which provides opportunities for students to explore the interaction of genotype with environment within an evolutionary framework, becomes an important theme.

Teachers can select activities from among the twenty-five included in the "Genes and Surroundings" program for a course in science, health, or interdisciplinary studies. The activities seek to relate knowledge about human genetics to the student's physical and social environment and to his or her personal growth, and include: analysis of fingerprint patterns; the study of individual talents and differences; models to illustrate the transmission of genes from one generation to the next; the preparation of pedigree charts; analysis of karyotypes; the development of physical models to simulate the phenotypic

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expression of dominant and recessive characteristics; the study of case histories of health problems that can be related to single gene or chromosomal anomalies; the construction of mythical creatures with identifiable inherited traits, and timelines to depict patterns of growth and development in humans and other animals; the identification of components of the environment and ways in which they affect people; the elucidation of the concept of adaptation in both the biological and the cultural sense, and many others.

High School and Adult Education—"Basic Genetics: A Human Approach," the program for this age group, is in the form of a "magazine." The materials—articles, interviews, human interest stories, news reports, puzzles, and cartoons—emphasize the physical, psychological, and social determinants of health and the decision-making options created by new knowledge and techniques in genetics.

The title of the program accurately reflects its emphasis on "biology for life and living."[30] Although students learn, as do their peers in more traditional classes, about gene segregation and assortment, blood types, pedigrees, genetic disorders, and frequencies and distributions of genes and genotypes in populations, in this experimental program these topics are presented from the human point of view. In the study of inheritance, human beings are nearly always studied in preference to the other animals. Perhaps the most important distinction between traditional texts and the new genetics instruction is the interdisciplinary structure of the curriculum. Students learn the principles of genetics not as ends in themselves, but as means of dealing with personal and familial concerns—genetic counseling and screening, prenatal diagnosis, family problems that grow out of handicapping conditions—and social concerns, such as the analysis of ethical issues as matters of conflicts between goals, rights, and duties, as well as contradictions in matters of social and public policy.

"Living with Cystic Fibrosis," a newspaper account of a fictional family, provides opportunities for students to begin thinking about most of the major topics in genetics that are presented in the program. Further study is devoted to the structure and function and chromosomes, gene mapping, the interaction of genotype with environment, the effects of natural selection and genetic drift on gene frequencies in populations, continuous and discontinuous distribution of traits in human populations, genetic screening, genetic disorders, techniques of prenatal diagnosis and the concomitant difficult choices that individuals and families often face, sources and rates of

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mutation, recombinant DNA techniques and research, and ethical questions.

No doubt there are other ways to teach biology and genetics. What we have presented is simply one way of doing so, but our intention was to show the strong links between school knowledge and the kind of useful information one needs in carrying on one's daily life. Scientific literacy—the public understanding of science—*is* essential not only in terms of the alternatives that affect individuals, but in terms of a public that must be able to evaluate the customs and institutions we live by. Without such competence we are at the mercy of all sorts of destabilizing influences. Such knowledge is not a luxury, a source of entertainment, or an aesthetic experience. It is a necessity.

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John G. Kemeny

The Case for Computer Literacy

THE WARNING OF ENGLISH physicist and author C.P. Snow that the well educated are splitting up into two cultures, that many in fact lack an understanding of science, is certainly applicable to the United States today. But while Snow deplored the indifference of the best educated to the Second Law of Thermodynamics, here we complain that most citizens do not understand even the most elementary physical science. Other articles in this volume will deal with the sad state of scientific literacy and with possible remedies. My task is to make the case for widespread computer literacy.

One is tempted to be extremely pessimistic: if, in spite of decades of trying to improve scientific education, most educated people are still scientific illiterates, what hope is there to achieve literacy in a field as new and strange as computer science? Will not the coming of computers make the split between the two cultures worse and limit computer literacy to a very small fraction of the population? After extensive thought, I have rejected that proposition and instead have reached an optimistic conclusion. On the one hand, I believe that computer literacy is even more important than scientific literacy; on the other, I am convinced that the former is much easier to achieve and that a substantial fraction of the population has a chance of doing so. I believe further that widespread computer literacy will help to solve the problem of scientific illiteracy.

THE NEED

Much has been written about the impact of the computer revolution and the fact that the number of jobs requiring computer literacy

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is increasing rapidly. Yet it would be a mistake to base the case entirely on past and present experience, because a much stronger case can be made for computer literacy in the future. In the next three decades, intelligence will be built into most manufactured objects, and those who lack even minimal computer literacy will have difficulty functioning in everyday life.

All machines, from automobiles to ovens, will contain microprocessors capable of a substantial degree of intelligence. But I foresee intelligence also being incorporated into all kinds of manufactured objects that would not normally be classified as "machines." An important example may be the intelligent house.

Since buying a home is for most of us our single greatest investment, providing our home with a fairly high IQ is merely giving it no more than its due. Although the savings in energy alone should justify the cost of a microprocessor, there is much more that an intelligent house can do to protect and shelter us, and to keep us informed and entertained.

A computer system can control the source of heat in a much more sophisticated way than can the old-fashioned thermostat. It can also monitor smoke detectors and burglar alarms, and make a thoughtful decision on whether to call for help. It can control all those gadgets and appliances that now have some primitive intelligence built into them, such as videorecorders, microwave ovens, and radio alarms. One should be able to program, in a vastly more flexible way than is possible today, all of the instruments at a single central station. Our home control computer, for example, can memorize all our favorite recipes, and then, provided with a menu and the number of people for dinner, as well as the time when dinner should be ready, it could tell us how much we need of each ingredient and take over the entire processing of the dinner, with each dish ready at just the right time. Or it can provide a flexible alarm system that wakes us at different times on different days, sometimes to FM music and sometimes to an early morning program on television. And the system must be intelligent enough to know that whenever we cannot catch "Hill Street Blues," the program should be videorecorded for later viewing. (The first videorecorder that has sufficient intelligence to skip commercials will make a fortune. Unfortunately, the recognition of commercials is a very difficult problem in artificial intelligence, since some commercials are more interesting than the shows they interrupt.)

The gadgets and appliances now being marketed represent "halfway technology." Since each is limited to the intelligence built into it,

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and to its own means of communication, manufacturers are achieving much less than is possible. Yet it would be prohibitively expensive for each household article to have the capabilities of a personal computer as far as logic and memory and the way it communicates with human beings are concerned.

The key breakthrough will be to have a central computer in the home, with the various household gadgets, the "peripherals," hooked into it. The occupants of the home will have the luxury of a sophisticated and yet friendly personal computer to communicate with, and will be able to use similar methods for regulating all the appliances. It will also make the appliances affordable, since the capabilities of the personal computer need not be duplicated.

The drawback to recent "high technology" appliances is that they are quite hard to use, and a variety of them in the home means that the user will have to become familiar with their different conventions and programming methods. Each one, of course, comes with its own instruction manual, and it seems to be a law of nature that the one you need is the one that has been misplaced. This is surely an absurd way of storing and retrieving information in the age of computers.

If manufacturers could be persuaded that computer literacy is spreading rapidly and that computers capable of running appliances will soon become common in the home, they will start designing appliances that are peripherals for these computers. Someday in the not too distant future, instead of each appliance coming with an instruction manual, it will be delivered with a computer program to be added to the repertoire of the home computer. Then it will be the computer, not the human being, that learns how the new gadget operates. Once the program is inserted, the occupants of the house would be able to give instructions to the new appliance in a language and style that have become second nature. Furthermore, the home computer, by taking adequate safeguards, could prevent us from making dangerous mistakes. Only the absence of a sufficiently large buying public, with enough computer literacy to operate a personal computer intelligently, prevents the realization of this domestic paradise.

While the control of gadgets may justify the expense of an intelligent home, its potential for enriching our lives is much greater. The processor can serve as a computer and a word processor. And a powerful computer in the home can be the source of first-rate entertainment. While today's video games give an indication of the potential popularity of computer games, all the intelligence is used for

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spectacular visual images and very little for the games themselves. But the most important use of our home computer will be as an information center.

Access to key information can often mean the difference between success and failure in many endeavors. In our complex world, it is difficult to have that kind of access without the aid of computers. Sooner or later this nation must—and will—come up with a design for a national information network that any intelligent home will be able to access.

What kind of information is likely to be available? First of all, news distributed through home computers will replace printed newspapers. It will be quite cheap to store an enormous amount of information, ranging from international news that one normally gets in the *New York Times,* to the kind of personal details found only in a small-town newspaper. Once we can get the news this way, we will also have available a sophisticated means for finding items of interest and for doing selective reading. For example, the computer could alert us to news on topics of special interest to us and, depending on what we wish to see, let us choose a summary, a brief account, or complete details.

Further, a home terminal should be able to access a network of information on merchandise available in neighborhood stores and the programs of various theaters. It will provide information on medical and legal issues that do not require the services of a doctor or a lawyer, and give you the voting record of your Congressman.

Education will be one of the most important uses of a home information center, for children and adults alike. The problem with adult education on television is that the "student" is purely passive. With a computer terminal, one can engage actively in a program of continuing education. This is particularly true for what is perhaps the most important use of such a system, access to the research and reference materials of the great libraries of the country. It will be entirely possible to search the catalogue of the Library of Congress from your home terminal and to read articles and books right on the screen of your terminal.[1] (I shall discuss education in more detail later.)

I have avoided using the word "robot" because artificial intelligence must make much greater progress before we have "R2D2" available to us. And I do worry about the day when household robots first come on the market; someone is sure to tell the robot to dump out the bath water and forget to tell it to remove the baby first.

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The problem of the baby in the bath water is very much to the point. Isaac Asimov has written most reassuringly about robots that have laws built into them to prevent their ever doing harm to human beings. I believe it is possible to do so—but we must first solve two problems: How does the machine recognize a human being, and how does the machine know what is harmful to human beings? A robot capable of recognizing a small mass of fat, uttering unrecognizable squeals, as a baby in the bathtub would be a very intelligent robot indeed.

The problems may not exist in the early stages when we will be provided with a small number of options within specified ranges for each gadget we own. But the whole point of programming a computer is to provide ourselves with vastly more freedom than we had previously. I am quite certain that we are going to *insist* that manufacturers provide us with that capability. The greatest satisfaction that can be had from a computer is to use it for something that the manufacturer has not even conceived of. And once we can do that, our home computer must either be intelligent enough to prevent us from making dangerous mistakes, or our home insurance policy is likely to have an escape clause not only for acts of God, but also for computer bugs.

If I am right that intelligent machines will invade the lives of all of us, then the need for comptuer literacy will be even more vital than it is today, and at a level of sophistication higher than that required for using a computer that merely calculates and retrieves information.

WHAT WILL HUMANS DO?

The Industrial Revolution fundamentally changed how most people in what became the modern world earn their living. From a society in which human labor was mainly physical, we have become one in which the majority of workers provide a service. Very few jobs now require exceptional physical powers, since machines can easily lift heavy weights, move much faster, and work longer hours than human beings. The coming of intelligent machines will further narrow the areas in which human beings excel.

A good example of this is how photoduplication, dictating machines, and, more recently, word processors have changed the secretary's job. And yet those changes are small compared to what the impact of an intelligent computer terminal will be. Most mail will be received electronically and filed in the memory of the computer.

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Hard copy may never be required, since any office having access to the information can always display the item on a computer screen. I would not dare to predict what sophisticated machinery will be available routinely to secretaries a generation from now. Many of their present skills will be irrelevant, and the secretary's most important asset will be the ability to communicate with intelligent machines and to make full use of their capabilities.

Today, universal literacy is demanded because the illiterate is unemployable, and indeed, has difficulty surviving. Someday computer literacy will be a condition for employment, possibly for survival, because the computer illiterate will be cut off from most sources of information. The human brain unaided by computers will appear feebleminded.

I have never been an advocate of "full automation" but rather of human beings and computers working as a team. We know the tasks at which computers outperform human beings; what we need to define are the tasks that are best left to humans. In the past, we have identified the traits unique to human beings by comparing ourselves to the higher animals. But that method of comparison is no longer satisfactory, because computers are even better at some of these "uniquely human" tasks. Just where the line is drawn between computer and human skills will determine not only how most people will be employed in the future, but what "human" skills will be most highly prized.

It is risky to speculate what these skills will be, but I will hazard a guess at some that are likely to be reserved to humans. First, although pattern recognition by machines will improve, I believe that, for some time to come, the best results will be obtained by human beings—assisted by computers. Second, computers will be invaluable in decision-making, but the final value judgments will be left to humans. And third, creativity will, for the indefinite future, be a uniquely human attribute.

Robert Jastrow ends *The Enchanted Loom*[2] with a gloomy picture of a future (not so far away) when computers will outperform human beings at all tasks. With all due respect to Professor Jastrow and his excellent book, I think that prediction is overly pessimistic. Computers will not catch up with us in all areas in the foreseeable future, and it is not obvious to me that they ever will. Biological evolution of the human race is entirely possible, but it is not our only defense. Thanks to the invention of the printing press, human beings advanced more in a few centuries than did most species in a million

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years. What capabilities will mankind develop once it fully masters the use of computers and intelligent machines?

COMPLEX SYSTEMS

The structure of our society has become so complex that human beings no longer seem able to manage its systems. The national economy, social security, higher education—we seem to make a mess of all long-range planning. Computers alone cannot of course solve the problems of planning for our complex systems, but neither can these problems be solved *without* the use of computers. Indeed, they require extremely sophisticated use. We need computer models, not only to answer our questions, but because in many cases, it is the model itself that helps to formulate the *right* ones.

The usefulness of computer models is still controversial; many of the existing models of complex human systems have flaws that are easy to identify—and therefore easy to ridicule. But the alternative is a set of hazily formulated assumptions, usually not even articulated, that may exist only in the mind of one human being. Since others do not have access to this "mental model," or only hear an extremely vague description of it, its flaws are much more difficult to discern. The only way to criticize it is by pointing out that the model leads to disastrous results.

To choose an example at random, I believe that such mental models characterize the way the Executive Branch and Congress think about the national economy, and about federal planning for energy, transportation, and health care—and not only are these models inadequate, but we seem to be making absolutely no progress with them. When something goes wrong, as it usually does, it is hard to pinpoint where the fault lies, and politicians can therefore blame the failure on something other than their own decision-making processes.

Computer models may appear risky to their users because their flaws *can* be pinpointed. Yet if one tests them carefully against experience, and tries to make an improvement every time the predictions turn out to be inaccurate, there will be significant progress in the long run. Anyone who doubts this should consider how far physics would have progressed if physicists had been limited to working in ordinary English.

But there are still more benefits from attempting to model a complex system by a computer program. Even the executive who thinks that he or she knows an enterprise very well may gain an entirely

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new perspective from the process of trying to model it. For this purpose, whether the eventual model is good, bad, or mediocre is almost irrelevant, for it is the discipline of describing precisely the organization's structure, and stating clearly the interrelationships between the various segments, that helps one to understand the enterprise better.

The modeling process itself will suggest a number of questions that have never been thought of before. During my years as president of Dartmouth, I gained a great deal from doing my own computer modeling. Sometimes the benefit was a highly useful model, but often it was a new line of thought or a new way of looking at the College that had not occurred to me (or to anyone else) before.

One tends to live with a number of "rules of thumb" that represent experience under "normal" conditions. As long as conditions are reasonably normal—whatever that may mean at the moment—one does not ask what combinations of factors have brought about the present situation and what new factors could change the situation dramatically. But if one attempts to build a computer model of the system, these questions are necessarily asked. Answering them turns out to be a valuable learning process, and sometimes the answers are vitally important.

Unfortunately, most decision-makers in government and industry today are computer-illiterates. Although computer systems are in place in most large organizations, they perform mostly routine bookkeeping functions and are used little, if at all, in decision-making. High-level executives, too embarrassed to expose their ignorance of computers by asking questions of the computing center, often leave important corporate decisions by default to computer programmers, who must fill in the gaps in the vague, general instructions they receive from top management.

A great deal of research needs to be done on computer modeling of complex systems, but research alone cannot solve the problem. Major organizations need among their senior decision-makers men and women who are computer literate and in tune with the computer age.

Nor is the problem limited to planning. Many of today's more complex pieces of technology are far behind the state of the art. From the control room of a nuclear power plant to systems of urban mass transportation, we find primitive levels of intelligence built into machines when the problem cries for highly intelligent equipment. Again, significant progress will not be made until we have a plentiful

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supply of human beings who are capable of designing, implementing, and operating large systems of artificial intelligence.

The United States is going through an extremely dangerous transition stage. Since most decisions in both the public and private sectors are made by individuals who were educated in the precomputer age, individuals who have not been able to readjust their thought processes, their fumblings are similar to what we would expect if a camel driver found himself at the controls of a modern ocean liner.

THE CHALLENGE

If we compare learning a computer language with learning a foreign language, we find similarities but also major differences. All languages are designed to express the same thoughts as in our own, using a different vocabulary, of course, and most often a different syntax. Learning a computer language, however, is more like learning to communicate with an alien, the essential difficulty of which is to adjust our thinking to the alien's.

The difference becomes even clearer if we compare learning a second foreign language with learning a second computer language. While there is no doubt that the second foreign language comes easier than the first, it still takes a couple of years to read and write the language at all well. In contrast, all the major difficulties are mastered with the learning of one's first computer language, and one can become reasonably expert in a second language within a month. Learning a computer language is not primarily a linguistic achievement; rather, it requires an adjustment in the way we think.

Achieving computer literacy, however, has its obstacles. Many grown-ups, for example, when forced to sit down at a computer terminal, exhibit the kind of fear that reflects the adult wariness of experiences that are new and hence "strange." But such fear is not innate, since children, who greet new experiences with anticipation and delight, take great joy in being allowed to use a computer, and seem to master its mysteries with remarkable speed.

But fear is by no means the only obstacle. Human language abounds in vagueness and ambiguity, features that are essential for human endeavors ranging from poetry to puns. Computers, however, require a precision of expression rare in ordinary language. In normal discourse we assume some shared experiences, and hence need not dot every "i" and cross every "t." (For this reason, individuals from drastically different cultures *do* have difficulty in communi-

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cating.) And we assume that the listener has common sense. Unfortunately, computers have not shared our experiences and have absolutely no common sense!

There are many simple examples. Using "legal" words and the correct syntax, we ask a computer to work out a long problem, but what we forget to tell it is that we want to know the answer, which the computer meticulously finds—and keeps a secret from us. (When I tell this story, I can always spot the experienced computer users in the audience—they are the ones who are *not* laughing. It has happened to us too often.) Or we assume, in speaking, that our listener will mentally correct small slips of the tongue, will guess the intent of dangling references and accept a wave of the hand or a facial expression for an omitted phrase. None of these works with computers.

A final obstacle is that we have to learn to think in terms of algorithms, which are precise recipes for solving problems or for accomplishing a task. A computer program describes an algorithm; it tells us "how to get there." Although algorithms were used and studied in mathematics in the past, there is today a strong prejudice in favor of formulas—that is, achieved results. But computers are forcing us all, even mathematicians, to readjust our thinking.

This is easier said than done, for we perform many tasks that we would find difficult to explain. Humans excel at pattern recognition, yet it is very difficult to teach this to computers. This is true whether one speaks of a numerical pattern, a geometric shape, or a piece of furniture. Children learn how to walk, but we would have great difficulty explaining to an alien species exactly what we do with each muscle.

That is why "easy" and "difficult" take on new meaning when dealing with a computer. The difficulty of writing a given computer program has less to do with the inherent complexity of the problem being solved (complexity as perceived by humans) than it has to do with how hard we find it to explain the method of solution to an alien intelligence.

LET THE PUNISHMENT FIT THE CRIME

For generations, mathematics teachers have preached to their students the necessity for clarity, precision, and logical thinking—and for generations, most students have failed to respond. One of the most common experiences in teaching mathematics is to have a student come up after a test and say, "I really understand the material,

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but I made some careless mistakes." Sometimes the mistakes are indeed carelessness, such as being wrong by a factor of ten, but at other times, the student thinks he or she understands the material but actually has missed an important point. What will these students do if they get into decision-making positions? Will a doctor get the dose of medicine wrong by a factor of ten? Will a business leader only *think* that he understands the needs of his corporation, and through a slight misunderstanding, bankrupt it? Will a decision-maker in government commit a small logical error and cause untold suffering to millions of people?

Whatever else computers may be good for, they are a marvelous means of counteracting the human tendency to be sloppy. A bit of carelessness in writing a complete program will result in a gentle message pointing out the error, in language simple enough for a human being to understand. A program that is based on "almost understanding the problem," or that commits a small logical mistake, will very likely result in a computer producing tons of results—all of them wrong. Computers, in short, are designed to let the punishment fit the human crime.

We humans suffer only slight embarrassment when others detect errors in our work, yet it is quite humiliating to be chided by an electronic box for carelessness, or after many hours of hard work, to have complicated garbage pouring out of the computer. For anyone who desires to learn computer programming, a few sessions with the computer will do much more to teach him or her about the necessity for precise logical thinking than any amount of human preaching could. One need not present a hypothetical case to show how a quite small mistake can ruin a very large project. Every computer programmer knows this from unhappy personal experience.

What are the skills necessary to become a good computer programmer? The first is the ability to express one's thoughts in a very simple language. A computer language like BASIC, with its small vocabulary and limited number of clearly defined concepts, is extremely simple compared to any human language. When beginners say they have trouble learning a computer language, what they really mean is that, although they can learn the language easily enough, expressing their needs in so slight a number of concepts is much more difficult. Most people write in a complex style primarily because they have trouble expressing their thoughts simply. One hears frequent complaints about this from the world of business, and the writing

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style prevalent in government is the subject of an endless number of jokes.

Once a programmer crosses this linguistic barrier, the next obstacle is to explain to the computer how to solve a problem—and to do so without appealing to shared experiences or to intuition. If, in instructing a computer, you use the phrase "you know," you will be in trouble, because the computer does *not* know—unless whatever the phrase refers to is clearly explained. In the process, the programmer will discover that he has either not truly understood the method of solution or is unable to articulate it clearly.

In teaching computer programming, we place great stress on the ability to divide complex tasks into small, clearly understood components. But breaking down a procedure into simple steps, and then being able to understand the precise, logical relation among them, is a skill that human beings seldom acquire. Yet once the skill is mastered, it influences the way a person thinks in all kinds of situations that have nothing whatever to do with computers. Here are two quite different examples.

First, let us consider medical diagnosis. A doctor giving an annual checkup needs to carry out a large number of small steps. These range from executing advanced procedures, such as electrocardiography, to looking carefully through the pupils of the eye, or simply talking to the patient. And if any procedure leads to results other than what the doctor would normally expect, further tests will be necessary. In effect, the doctor is working his or her way through a complex algorithm, where future steps depend on the outcomes of earlier tests. Since most tests are not in themselves conclusive, to reach a reasonable diagnosis the doctor must understand the interrelations between a large number of small steps. Although some physicians are able to diagnose a wide variety of illnesses accurately, "bugs" in medical procedures, leading either to an erroneous diagnosis or the failure to spot a disease, must be quite common. How far computers can go to help doctors in their diagnosis is a fascinating topic. However, this is not my current concern. Instead, I am suggesting that the doctor who has had serious exposure to computer programming is likely to be a much more successful diagnostician.

Next, consider an executive managing a complex enterprise. It is axiomatic that the executive must learn how to delegate—to divide each job into a number of separate tasks, assigning many of them to other individuals, and explaining clearly what is expected. In a large organization, delegation may proceed to the next lower level, then

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the next, and so on. This is similar to writing a large computer program in hierarchical form, where, through several levels, larger tasks are divided into smaller ones, always making sure that the communication, both "from the top down" and "from the bottom up," is good.

The most annoying problems seem to crop up about three levels below the chief executive, where there may be someone who does not understand the task assigned and how it fits into the overall goals of the institution, or where two people are working at cross purposes, or where the chain of communication has broken down. A period of serious exposure to computer programming would, I think, improve the quality of managers.

Finally, a skill that all computer programmers must acquire is "debugging." For a large computer program, consisting of several levels of smaller and smaller tasks, one must be able to infer, from the overall program malfunction, where to look for the source of trouble, and if the answer is not clear, to work down the hierarchy until the "bug" is found. The acquisition of such skills would be invaluable for those charged with the management of complex systems, particularly organizations of human beings.

In sum, learning computer programming has a beneficial effect on human thinking, because it teaches skills that are fundamental to most professions.

A NEW CONCEPTUAL FRAMEWORK

In the major challenge to computer scientists, that of enabling millions of people to program intelligent machines, discussions tend to focus on the significant improvements that have been made from early—and primitive—computer languages, or the relative merits of currently popular languages. I would like to focus the discussion instead on the emergence of *new types of concepts* within languages.

The early languages were designed to deal exclusively with arithmetic and primitive logic. As computers acquired large memories, they had to be able to read and write files. With the coming of time-sharing, users were able to interact with computers while their program was running; thus computer languages had to include commands that allowed two-way communication. Still later, when graphics terminals became easily available, concepts had to be added to languages for the drawing of pictures. I cite these developments,

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because I believe that to enable computers to manipulate all kinds of machines, an entirely new set of concepts must be invented.

Another trend has been to improve the structure of languages. A good language both makes it easy for a beginner to start writing programs and accommodates the needs of the advanced programmer. The development of "structured languages" in recent years has been a giant step forward. A good structured language helps an inexperienced person avoid many of the usual kinds of mistakes and helps the expert to write a large, complex program that is readable and reasonably easy to debug.

Yet not all the developments have been favorable. Complexity usually brings chaos in its train. In computer graphics, the lack of standardized terminals is a great nuisance. Furthermore, it is not reasonable to expect everyone to become expert on the peculiarities of particular devices, for all freshmen, for example, to learn the idiosyncrasies of the various kinds of graphics terminals available on campus. The complexity we will face when computers have to manage a variety of machines will be far worse than any problem we have solved so far. One possible solution lies in the ingenious way graphics are handled at Dartmouth.

BASIC at Dartmouth is a highly structured language of great power, with simple commands for drawing pictures built into it. These commands cover the commonest features available on graphics terminals and can be used easily by beginners. The user may, by a single command in the program, specify the kind of plotting device he or she is using. If the same program is to be run on a different device, only one line need be changed. This simple solution works because systems programmers have written a set of routines for each kind of graphics terminal the college has acquired. These routines translate the graphics instructions into the special codes that activate the drawing of pictures on that particular terminal. By specifying within the program the name of the terminal, the system knows which particular set of routines to provide for the user. If an entirely new terminal comes along—which happens frequently—the sole requirement is for one programmer to write a new set of routines. The new terminal can then be used by someone simply inserting its name in the appropriate place in the program.

Could such a solution work for communication with intelligent machines? I can conceive—at least vaguely—of a conceptual framework rich enough to allow communication with arbitrary machines. One could build appropriate commands to cover these concepts into

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a language and then leave it to systems programmers (or to the manufacturers of particular devices) to implement routines that apply these concepts to a particular machine. Thus the same home computer, using the same computer language, could be used to instruct an oven, a TV recorder, a burglar alarm, and an information retrieval system. The major breakthrough that is necessary is to invent a new conceptual framework, a challenge that I predict will be far greater than any we have faced so far.

EDUCATION IN THE COMPUTER AGE

Once computers are available in the classroom, we will be forced to rethink what to teach and how to teach it. First, the right way to solve a problem may be different in the computer age. Second, certain traditional topics have become useless. Third, the computer is a powerful tool for solving problems, available both to the instructor and the student. Fourth, programming a computer is an important learning experience for the programmer. Points one and two affect *what* we should teach to students, while three and four should drastically change *how* we teach.

Although some topics are taught for their intrinsic value, many of the things we teach, at all levels of education, are means to an end. And since these means were designed in the precomputer age, a good many have become obsolete. Why teach the "skill" of interpolation in a trigonometric table, when the value of a trigonometric function can be found in ten seconds on a pocket calculator? Once the student is freed from this arithmetic bondage, it is much more likely that he or she will understand the principles of trigonometry and learn to enjoy them.

Again, the most hated portions of a calculus course deal with messy techniques that were necessary in an age of hand calculation, as, for example, the many steps required to arrive at a numerical value for a complicated definite integral. But there is no justification in teaching these transformations when a computer can find the same numerical value in a fraction of a second. A modern calculus course should concentrate on the fundamental concepts of the calculus—which are among the greatest creations of the human mind—teach only the most basic techniques, and lead the student to the appropriate computer programs for obtaining answers.

We can revolutionize the teaching of sciences by substituting the power of the computer for the memorization and application of

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complex mathematical formulas. Although knowledge of the basic concepts of the calculus is necessary to understand Newton's laws, students poor at arithmetic or algebra should not be discouraged from pursuing the physical sciences. While differential equations frighten many students, a computer program that incorporates the laws of motion and gravitation is much simpler to understand. And spending an hour in front of a computer screen trying to put a satellite into orbit around the earth, or landing a space ship on the moon, will do vastly more for a student's physical intuition than trying to solve complicated equations—a particularly good example, since the complete solution of the path of a rocket is not possible without a computer. Nothing is gained by taking the student through very complicated calculus-type arguments before turning to the computer. For such reasons, computer literacy cannot help but bring about a much wider understanding of the principles of physical science.

So, too, with the teaching of the biological and social sciences. Much of the latter deals with the retrieval and analysis of vast data bases, techniques that the modern computer enables elementary students to master. A freshman sociology student who already knows how to use computers can in one term learn an enormous amount about the formulation of hypotheses and their testing against actual data. In a sense, the computer provides a laboratory for the social sciences and allows the instructor to concentrate on basic principles and major techniques, rather than drilling the student in messy statistical procedures involving arduous, time-consuming calculations. And for the first time, it allows students to check the conclusions of "experts" and to demand that sweeping assertions be backed up by facts.

How will the methods of teaching change? It will no longer be possible—or desirable—to teach a mathematics course without giving computer demonstrations in the classroom. In the courses I teach, I use the classroom terminal for working out significant examples, rather than the usual trivial ones, to enable me to teach important applications and to walk the students through the steps of a complex algorithm. And a computer-drawn graph is worth a thousand words.

I can ask my students to use the same programs to solve problems, to modify the programs to handle different applications, or to write programs of their own. Programming is an invaluable learning experience, a point that cannot be stressed too strongly. Even after more than three decades of teaching, I acquire a deeper understanding of well-known techniques by writing a computer program for them.

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For students unacquainted with the technique, it is an even more important learning experience. Something as familiar as the quadratic formula takes on new meaning if one is forced to write a program. The so-called formula is shorthand for three entirely different cases that must be treated completely differently. This fact has confused generations of students. Since one is forced in a computer program to identify the cases clearly, and to treat each by an appropriate method, the student arrives at a clearer understanding of the quadratic formula than did most students in the past.

As I said before, we must break away from an emphasis on formulas, or achieved results, for in most cases, teaching the algorithm—the method of *achieving* a result—is what is important. Instead of stressing that equations of higher degree do not have formulas similar to the quadratic, we should teach a simple method that will find the roots of any equation, to any desired degree of accuracy.

A colleague of mine developed a probability theory course for sophomores that enables them to learn topics usually reserved for more advanced courses. The secret is the use of the computer to build up a student's intuition about probability and to enable him or her to apply advanced mathematical techniques.

The greatest hindrance to moving rapidly to the stage where computers are regularly available for the teaching of all science courses and many social science courses is not the cost of the equipment, but the need to train and retrain teachers to use computers competently and to be comfortable in their use in the classroom. With a computer, human beings can share in the vast accumulation of knowledge, not just in the sense of information retrieval, but in being able to use problem-solving techniques developed by others.

The computer's single most important impact on education will be in allowing the student to participate much more actively in the educational process. In much of education, the student is a passive absorber of knowledge, and there is only an occasional opportunity to work out a "canned" exercise. When spending hours at the computer terminal becomes a routine part of education, the student will be an active participant, able to initiate changes and influence the direction of his or her education. At no level is this more significant, perhaps, than in adult education. If the home computer can be used in conjunction with lectures on television or videotapes, many of the current weaknesses of continuing education will disappear. And we can look forward to still greater technological breakthroughs that will further revolutionize the educational process. At some point, a mar-

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riage will occur between personal computers and videodisc technology, allowing a richness of sight, sound, information retrieval, and computing power whose full effects none of us can foresee.

There are of course some bottlenecks to be overcome. Inexpensive computers are now widely available at the precollege level, but the software is often very poor. It is therefore essential that manufacturers of good, inexpensive computers provide standardized versions of one or more of the popular teaching computer languages. Once this happens, first-rate teachers will find it worthwhile to develop high-quality educational software, not only for the improved teaching it will afford, but also for the substantial financial benefits. The writing of good software may in the future become as lucrative as the writing of textbooks has been during the last few decades.

We must also accelerate the training and retraining of teachers. But just as good textbooks help improve the teaching of a weak teacher, good software can play the same role until a sufficiently large corps of trained teachers is developed. On the college level, much more rapid progress should be expected.

Many colleges now offer an elementary introduction to computers. A question frequently asked is whether such an elementary introduction suffices, and if not, how room for further computer courses in an already overcrowded curriculum can be made. We can answer this question by comparing the achievement of computer literacy to that of writing skills. Although freshman English is very important, it cannot carry the total responsibility for the teaching of writing. Unless there are courses throughout the curriculum that assign a substantial amount of writing—and in which professors are willing to hold students responsible for doing it well—the majority of graduates will write poorly. Similarly, if computer assignments are routinely given in a wide variety of courses—and faculty members expect students to write good programs—then computer literacy will be achieved without having a disproportionate number of computer science courses in the curriculum.

Where a good time-sharing system is easily available to faculty and students, the rest happens almost automatically. But there is still enormous diversity in the computer capabilities available for instruction on various campuses. Many years ago I proposed that the lack of adequate computer capability should be cause for a college to lose its accreditation, just as an inadequate library is today. But my suggestion has not been implemented. Accrediting committees are very

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conservative, particularly when a new rule might mean disaccrediting some very famous institution.

Initially, we all guess that only students with an interest in mathematics and a demonstrated talent for it will be good at computers. But the evidence is overwhelming that computers may appeal to students who have never shown any talent for mathematics and, indeed, may have hated the subject. I knew a religion major at Dartmouth, with a strong antiscience bias, who became a computer scientist.

We are going through a difficult bootstrap operation. A generation untrained in computers is trying to introduce this powerful new technology into the classroom and to educate a new generation that will feel completely comfortable in the computer age. It is essential that we rethink what is worth teaching today and how we can improve the process of instruction by means of computers. I hope that the federal government and private foundations will be prepared to underwrite the very substantial transition costs, and that computer manufacturers will be enlightened enough to see the enormous long-term benefits they can achieve by helping to accelerate the spread of computer literacy. The transition to full use of computers and intelligent machines is inevitable. Our only choice is whether, through intelligent reform of our educational system, we make the transition a relatively painless one.

AN OPPORTUNITY FOR MANKIND

One proposal for achieving computer literacy is to enable users to communicate with computers in "ordinary language." I consider this a mistake and am worried that mankind will miss a major opportunity. No, I have not changed my mind about making systems easy and pleasant to use, but the substitution of ordinary language for simple computer languages is *not* a step in the right direction.

Ordinary languages have developed, without any particular rhyme or reason, through a long series of historical accidents. Vaguenesses and ambiguities are tolerated, and grammarians are more interested in history than in logic. The extensive drilling in their native language that students receive at an early age may be wonderful preparation for the appreciation of literature, but it teaches them very poor habits for scientific thinking. The early introduction of a computer language might be a healthy antidote.

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To some extent, this counterbalancing role has been played historically by mathematics. It is called "the language of science," and students are warned not to attempt the more rigorous sciences without first acquiring a strong mathematical background—which, unfortunately, takes a discouragingly long time. Yet children are learning computer programming at a remarkably early age, and loving it. Therefore, while ordinary languages will continue to be used for daily discourse and literature, and mathematics will certainly remain an important subject, much more of the teaching of mathematics and science should be in the language of algorithms, and hence taught as computer programs.

We have a unique opportunity to improve human thinking. If we recognize the areas of human knowledge where ordinary languages are inappropriate, and if computer literacy is routinely achieved in our schools, we can aspire to human thought of a clarity and precision rare today. This development would be of immense value for science, for the organization and retrieval of information, and for all forms of decision-making. Forcing humans to develop such thought processes may be the major fringe benefit of the coming of computers.

One of the oldest dreams of mankind is a universal language. It is notable that computer languages seem to cross national boundaries without difficulty. Thus the first universal language may turn out to be neither English nor Esperanto, but a language like BASIC.

ENDNOTES

[1]I first proposed such a system in a talk at M.I.T. in 1961. For a later discussion, see chapter 8 of my book, *Man and the Computer* (New York: Scribner's, 1972).
[2]Robert Jastrow, *The Enchanted Loom* (New York: Simon & Schuster, 1981).

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Stephen R. Graubard

Nothing To Fear, Much to Do

EVEN THE MOST CASUAL EXAMINATION of this issue of *Daedalus* will suggest that the term "scientific literacy" lacks all precision, that there are no generally accepted criteria for determining what an individual needs to know to be called scientifically literate, or why it is vital (or even important) for great numbers of Americans to wish to achieve such literacy. Basic competence in science—another way of defining scientific literacy—is clearly an elusive concept, made all the more so by a fundamental ambiguity, even among educators, about the kinds of scientific knowledge and understanding that it is useful for ordinary citizens to command. Given these uncertainties, it is scarcely surprising that there is so little agreement today about what the nation's broad scientific educational objectives ought to be or what strategies might be most useful in realizing them. If it is unreasonable to aim for anything like universal scientific literacy—defining that term in the simplest way imaginable—it is important to know whether the objective is shunned because it is utopian, because many believe that the nation lacks the human or material resources to achieve such an end, or whether it is simply felt that so bold a purpose is neither economically nor politically necessary. It matters profoundly whether the judgment reflects a hardheaded decision about student capability and teacher availability—about expense more generally—or whether it derives from an unconscious neglect even to consider the possibility of institutionalizing new types of educational opportunity.

Given the conventional view so often expressed about the benefits likely to be realized from a significantly expanded scientific literacy in the population as a whole, it is difficult to believe that fiscal necessity alone deters the society from making the substantial effort that a

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venturesome educational program designed to reduce scientific illiteracy would entail. The suspicion grows that it may not be money that is so lacking as will, or, to put the matter more generously, the capacity to understand what scientific illiteracy on a wide scale tells about the condition of American education more generally, what it reveals also about the capacity of this generation of Americans to ignore its problems, and when it does trouble itself about them, persistently to seek to resolve them with tactics more appropriate to a war against Hitler than to the world as it is at present constituted. In the way the country is now proceeding, in the modesty of its educational plans and ambitions, nothing may be revealed so much as timidity, intellectual fatigue, an incapacity to confront certain truths about itself.

With traditional literacy—the ability to read and write—there is less open national self-deception. While it may be difficult to teach these subjects, their necessity and centrality is generally accepted. Indeed, there is also a certain acceptance of the criteria that can be used in setting literary standards. When, for example, after World War II, UNESCO defined literacy as the individual's ability to "read and write a short simple statement on his everyday life," that definition expressed a specific, realizable objective. Those who found such a standard too low, who believed that a higher level of achievement was necessary, came forward with the idea of "functional" literacy. Such literacy, defined as the capacity to read and write so as to be able to function effectively in the group or community to which the individual belonged, implied various levels of accomplishment. It is not wholly surprising that a more simple, more embracing formula—the completion, for example, of a certain grade level in school—won favor with others. In a time of compulsory schooling, such a qualification could be easily met; it gave promise of making almost the whole population seem literate. It was a wonderful mask, particularly for those who wished to conceal or minimize the extent of the nation's illiteracy.

There are no equally convenient ways to disguise scientific illiteracy. A simple formula, on the UNESCO model, objectively testing scientific capability, seems impossibly difficult to construct. The principle that there be no single standard—that the individual's situation in life be considered—reeks of elitism. As for the idea of equating scientific literacy with a particular grade level in school, that criterion tells almost nothing of what the child has studied (or learned) of mathematics, general science, or any of the individual sciences. In

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this situation, it is not wholly surprising that the term "scientific literacy" has come to be associated with a set of vague and diverse capabilities: a demonstrated understanding of the nature of scientific method; an appreciation for the nature of scientific evidence; a knowledge of certain elementary principles of specific sciences.

In the absence of any agreement about the kinds of scientific knowledge sufficient to demonstrate literacy, one may well ask why the concept is used at all, why it is not simply abandoned. Why worry about scientific illiteracy when there are no agreed-upon methods for testing scientific literacy? The answer, quite simply, is that these terms are used heuristically; their purpose is principally to draw attention to a situation that is universally acknowledged, that no one knows how to cope with. *By even the most elementary standards, instruction in the sciences in most schools for most Americans is minimal. Science is avoided—evaded—by the preponderant number of American schoolchildren. That evasion is permitted to continue in the universities.* Why not say this? Why dwell on scientific literacy and illiteracy when such terms have so little specific weight? Because no other words will serve as well; they are deliberately chosen, principally to sound a political tocsin. In a world where illiteracy, like disease, is supposed to be disappearing—particularly in advanced countries—the idea that this is not happening at all in the United States, that the American people remain overwhelmingly illiterate in this vital area, is intended to be a disclosure shocking enough to generate a political reaction.

The question of whether conditions were ever better, whether scientific literacy, in any meaningful sense of the term, was ever more common, is largely irrelevant. For those concerned with the matter, it is not important whether the level of illiteracy has remained stationary, or has risen or fallen; their interest is principally to show that the American level remains substantially higher than those that obtain elsewhere, and that this condition cannot fail to have important debilitating consequences for the country.

If the concept of scientific literacy lacks precision and is used mostly to shock, to raise public awareness, that heightened awareness needs to focus on a specific need. What is the nation told to be afraid of today? The answer, increasingly given, is the industrial competitiveness of other advanced societies. We need to educate American youth, we are told, so that American industries will remain technologically competitive with those of Japan and of certain other heavily industrialized societies. This "new" political battle cry of many edu-

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cational reformers has refurbished the arguments of the 1950s to serve a new purpose. The alarm once generated by the Soviet launching of *Sputnik,* which led to vast new federal expenditures in education, is recalled, but in a quite new context. We are urged, in the words of Senator Paul Tsongas, to "modernize" America's educational system "so that it can meet the high-tech era's demands." We are told by the same authority that "we need an initiative on the scale of the Morrill Act of 1862, which established the land-grant colleges and helped make American agriculture Number 1." In this new educational venture, there is to be "joint sponsorship of educational programs by industry, states, and schools. Federal aid should be provided for training and retraining teachers so there will be enough of them to teach math, computer science and other subjects of technological importance." Finally, the Senator from Massachusetts recommends the creation of "a self-supporting Federal Education Bank, which would loan money to those needing assistance for university studies or vocational training."[1]

Would any responsible educator think to take issue with such bold and generous proposals? At a time when shortages of math teachers are said to exist in forty-three states, when comparable shortages in physics are reported in forty-two, and in chemistry in thirty-eight, federal assistance to alleviate such serious problems cannot fail to appeal. The same must be said of the idea of student loans guaranteed by the federal government. What educator would wish to argue against such federal expenditure? Even the idea of a new "partnership" between industry, states, and schools, all working for the same ends, sounds a novel and compelling political note. It promises a massive new federal program of aid, a new high-technology Morrill Act, with prospects for American industry no less bright than those created for American agriculture by act of Congress more than a century ago. Who can doubt the importance of such proposals? Who can fail to applaud what appears to be such enlightened policy?

Yet, there is residual concern, some lingering doubt whether all such grants are not predicated too much on an exaggerated fear of Japan (and a few others) and whether too much is not being promised the American public when and if certain teacher shortages are made good and computer literacy becomes more common. Only recently Americans were told how Russian children were habituated to passing many years in intensive study of science and math. The implication was clear; the Soviet military advantage, in some degree at least, was thought to be tied to a rigorous and demanding education-

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al system that Americans would be well advised to take note of. Less is heard of this argument today, in part because there may be some reluctance in certain quarters to draw attention to Soviet military capability, but more significantly, perhaps, because it is realized that such military capability probably owes little, if anything, to a superior Soviet educational system. Nineteen eighty-three is not 1958; arguments used then are not equally persuasive today. While appreciation of Soviet military strength is very real in most parts of the world today, Soviet military capability is not taken to be a proof of other Soviet accomplishments. The Soviet Union is too well known to appear a model industrial society. In its perpetually ailing agriculture, overburdened health care systems, primitive communications and transport—indeed, in the general disarray of much of its civilian economy—the Russians show sufficient ineptness to make even those who are most admiring of their incontestable military accomplishments think twice before giving excessive praise to their educational system. Few in the United States are urging Americans to "go to school" in the Soviet Union, to see how science should be taught, how scientific literacy on a wide scale can be achieved.

The same does not hold true of Japan. That country, for the moment at least, has what can best be described as substantial "industrial charisma." Whether the patina will not soon fade—whether it will not be seen to be little more substantial than that of certain European countries, recently believed to be major industrial competitors—it is impossible to say. The Japanese, in a wide range of industries, old and new, appear threatening. In these circumstances, it is not surprising that Americans pay heed to the Japanese educational system, imagining that in its rigors and precision there must be at least a partial explanation of the quality and reliability of the Japanese work force. The Japanese industrial success is so incontrovertible as to throw into relief an American industrial performance that seems mediocre by comparison. Inevitably, questions are raised about whether the United States must not seek to copy Japan, abandoning its old easygoing ways, acknowledging its educational sloth. What other options can the country be said to have?

While the evidence of Japanese technological prowess are striking, it is in fact not at all obvious that this success is linked principally to an educational system that Americans would do well to imitate, assuming always that they could. What, for example, would Americans choose to copy? Would they impose greater competitiveness in their schools? Would the school day and school year be extended?

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Would scientific subjects be given a more prominent place in the curriculum? At the expense of what other subjects? Would student failure become common? Would it be openly acknowledged as failure? Is the price of "scientific literacy" a greater realism about competence? Are these reasonable solutions for America's educational problems? Or, is it important to recognize that if the Japanese scientific educational system for the ordinary student is indeed superior, it may be tied to institutional and intellectual influences that are not at all exportable. How, for example, shall one establish in the American school the respect the Japanese show for memory, a faculty exercised from an early age by children obliged to learn to read and write a language with several thousand characters that have to be committed to memory? Where, in America, is the analogue for the Japanese mother, prodding her children, knowing that in Japan there are no "second chances," that competitive examinations are everything, that status later in life depends in great part on performing well in school? Are such things, in anything like the same form, conceivable in the United States? Would such an open "meritocracy" be tolerated here? For anyone even superficially familiar with American history and culture, the answers are all too obvious.

At a time when basic educational reform could be contemplated—when fundamental changes in consonance with American traditions might be tried—reform is defined largely as the injection of federal monies to train science and math teachers, to goad schools and universities to commit their own resources to instruction in scientific and technological subjects, to finance the education of those prepared to study these necessary but difficult subjects. How else would a politically motivated federal legislator think to remedy a condition that appears to be leading to the bankruptcy of vast numbers of American business firms, threatens whole industries, and produces massive unemployment and huge deficits in international trade? A characteristic twentieth century intellectual mindset—which Americans have no wish to abandon—is used again, principally to instill fear. We still have time, but not a great deal. We must do something at once. If we fail to act, something terrible will happen. Some version of this argument, it is imagined, is the intellectual fuel that can be depended upon to set the federal money engines going again. No other will do.

So long as these things are believed, there is little prospect of the country becoming seriously preoccupied with its more fundamental educational problems: *that scientific knowledge and understanding,*

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by any reasonable standard, is so uncommon among Americans of all ages and races today that it is no exaggeration to speak of mass illiteracy in the sciences. Why should that condition cause concern? For those who believe that such widespread illiteracy principally impedes productivity, that the quality of the American work force is diminished by such illiteracy, this is the only problem that needs to be attended to. Instruction in the new technologies—symbolized by the computer—is the required new educational agenda for all. For those who believe otherwise—who believe that the evidence suggesting that America's industrial problems derive substantially from insufficient technological instruction is at best inconclusive, and that only additional research can demonstrate the truth of the proposition—much larger issues are opened up. Their questions are unsettling, and it is easy to brush them aside precisely because they are so oblivious to the mass media's version of the most current crisis.

They begin by asking why ignorance of science is so much more damaging to the individual or society than an equivalent ignorance of other subjects. Would there be equal concern, they ask, if it were established that Shakespeare is incomprehensible to most Americans, or that the greatest number who frequent the country's museums and galleries, gazing at painting and sculpture, have only the most rudimentary understanding of what they are looking at, and that many millions more never go at all? Does it really matter that money and banking remains an arcane mystery for tens of millions, not only for those who have difficulties balancing their checkbooks, but for millions more who have no accounts to balance? Does anyone pretend that it is necessary for all to be instructed or interested in such matters? If not, why should ignorance of biology, astronomy, chemistry, physics, or mathematics be thought so much more serious? How does it differ from analogous ignorance of literature, art, or economics? Is there indeed conclusive evidence to show that an advanced industrial (or postindustrial) society requires great numbers of men and women educated in the sciences? Is this America's great intellectual lack? Are comparable insufficiencies in the education of children and adults in humanistic or social scientific subjects substantially less damaging? Has it been demonstrated, for example, that work efficiency is tied to scientific capability, that scientific illiteracy seriously impedes the careers of significant numbers of men and women, and that the economy of the society is hampered by these conditions?

To ask such questions is to complicate the issue, to make it appear that what may be most urgently needed today is not so much a tech-

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nical fix that will bring more and better science teachers into the classroom, prepared to instruct a greater number of interested students concerned with their future employ, as a more systematic inquiry into educational conditions that obtain generally in America's schools at this time, and how they affect American self-perception and understanding. If America's anxiety originates principally in distress with the Japanese economic challenge to this country, contributing to feelings of insecurity and doubt, that sentiment needs to be exploited to the advantage of America's schoolchildren. Teacher recruitment policies that would alleviate inequities and inefficiencies in the present system, perhaps also significantly improving the quality of instruction, are obviously deserving of support. The question, however, is whether such programs touch the fundamental public grievances of our day, which may have little to do with whether math is being taught well or badly, physics scarcely at all, or even whether computers are being purchased in sufficient number by economy-minded school boards. The present discontent in great parts of the country almost certainly reflects an acute disquiet with what is seen as the virtual collapse of public education in many places, together with the systematic mocking of a traditional American ideal, which involved more than simply making educational opportunity available, presuming always the maintaining of quality and excellence. If there is not even the pretense of quality in too many of America's schools today, it is reasonable to ask whether the present concern with foreign competition cannot be used to serve a larger purpose—the revival of America's faith in schooling, achieved through a new commitment to public education.

The idea that there are in this country today two systems of education—one essentially for the rich, safely and comfortably ensconced in their suburban ghettos, using public or private facilities according to their whim, able to choose on the basis of availability and quality, and another essentially for the poor, prisoners of urban slums, children who are warehoused in school and kept off the streets, taught "basics," if anything, preparing for what may prove to be years of unemployment—touches only the superficial surface of the educational injustice that cries out for remedy. Until a more deliberate effort is made to show how millions are cheated by today's educational system, that the greatest number of these are not slum dwellers, that most are neither black, Chicano, Puerto Rican, American Indian, nor recent immigrants, and that the educational system is today flawed in many of its parts, with notable exceptions of course

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in the public sector as in the private, sometimes in the inner city, sometimes in the suburbs—until such time, we will go on imagining that the problem of literacy is principally local, that it has to do with a "culture of poverty," that unwed mothers, abandoned wives, and feckless husbands create our major educational problems. They do not, though their contributions to the social pathologies of our time may indeed be substantial.

If scientific illiteracy is common today, it is because America's schools and universities permit the condition to exist, indeed perpetuate it. Until a more conscientious effort is made to understand how educational institutions, in collusion with students, tolerate the evasion of science, making science appear an arcane mystery, comprehensible only to a few, necessary only for certain occupations and professions, the true extent of contemporary American educational disingenuousness will never be seen. The same unwillingness to insist on a significant level of literacy in science extends into other subjects—foreign languages, for example—also thought to require special effort. Children are not encouraged to be competent in science because it is assumed that many or most are incapable of making the effort that achieving a modest competence would require. The disgrace of America's schools is not that the educational effort has been made and failed—that students have proved themselves incompetent—but that it has been rarely tried. Modern science is thought to be beyond the intelligence of ordinary children, of whatever class or race. The rudiments are given, occasionally; otherwise, children are free to choose "softer options," made so by the unconscious contempt of those who believe science to be too difficult.

While it seems entirely reasonable for boys and girls of sixteen to be instructed in learning how to drive an automobile, and for schools to assume a major responsibility in providing that instruction, equivalent instruction in science, leading to an equivalent sense of competence, is not thought essential. Why not? Because instruction in science is fashioned for the few, for those who actively desire it, who imagine themselves pursuing a career in medicine or engineering, pure or applied scientific research or teaching, where such knowledge is presumed both necessary and useful. What a travesty on the putative "uses" of what must be recognized as one of the most significant explorations of the human mind in this century. Science is treated almost as a mystery, a luxury that one chooses or refuses without serious loss to oneself.

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Such an attitude probably reflects not so much an active disdain as a misplaced sympathy, a kind of "kitsch" sentimentality for children and young adults unable or unwilling to master the essentials of difficult subjects. Behind the sentiment, however, there may also lurk a measure of self-contempt, even of fear, not least by those who are setting the standards. For a teacher to keep active children quiet and attentive in a classroom today is no small feat; to show oneself "cool" before violent, foul-mouthed, rebellious adolescents requires yet another kind of intelligence and courage. Neither capacity, however, is to be equated with that which makes a teacher able to communicate the essentials of a difficult subject, giving the student some sense of how much he has understood, how much he has failed to take in. To teach science well, at any level, calls for great skill. To learn science, beyond the most rudimentary level, demands effort, attention, and precision. It would be difficult to imagine any attributes more useful to an individual, whatever his intended occupation or profession. In theory, other subjects, "softer options," serve the same purposes; in fact, they rarely do.

Why, then, have schools and universities been so lax, so ready to accept illiteracy in science and in other equally demanding subjects? Why, in short, has the student mood been so relaxed for so long? Why does the condition persist today, despite the alarms increasingly sounded about the importance of academic achievement for job security, the growing concern about "downward mobility" for great numbers of middle-class youth, and the grim employment prospects for those condemned to live in urban ghettos, often forced to contend with racial prejudice as well as with insufficient training? Why do these several conditions—each affecting millions—not produce major political repercussions?

The answer, quite simply, is that these conditions do not produce a "crisis"; they do not announce an imminent upheaval. While some say that there is a good deal of cynicism in the country, and much "back-turning," a more convincing argument might be that "success" remains the country's only stable currency, achieved in some fields as much through "conning," through personality, pulchritude, and connections, as through intelligence, training, and education; and that in a society where so many find places at the top, where so few show evidences of clearly superior talent, where the avenues to success are so various, where second, third, and fourth chances are so common, and where money is so frequently the principal measure of achievement, education, in the more traditional sense of the term, is

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thought to have only limited utility. It is not that individuals disdain admission to the best universities, that competition is not rife, but admission even to so-called elite institutions generally reflects something other than a record of examinations brilliantly passed. In lesser institutions, even the pretense of academic excellence is generally absent; training replaces education, and training may have sufficient utility to stand the individual in good stead for years or even for a lifetime. In a large continental society like the American, it is very easy to be lost; it also quite easy to find a place. The gifted almost always do; so, also, do many others.

Why, then tamper with the system? Why not acknowledge that it works, at least for all but the most seriously disadvantaged in the society? The answer, quite simply, is that it may no longer be working. It is not that the Japanese (or the Germans) are breathing down America's industrial necks, that the Soviets are making American defenses seem insufficient, or that certain other countries are giving Americans a sense of inadequacy or inferiority. None of these conditions creates the nation's problems; none produces the malaise that is so much written about today and is so palpably felt by so many.

How, then, is one to explain the country's present discontents? Is it possible that the disjunction between the country's pretended values and the reality that intrudes each night through the television screen, highlighting certain of the darker features of the American landscape, has become too great? For better or worse, American democracy was intended to produce a "new man." Nineteenth century Americans, who so shocked European visitors with their arrogance and pride, their loud and bumptious talk and perpetual strutting, seemed to proclaim more than just a political independence from the Old World. Tocqueville interpreted the restless energy, the bombast and the sharp dealing, the rapid building of cities, towns, bridges, canals, ports, and all the rest to be evidence of a new kind of creativity, based on a new kind of value—equality. The "passion for equality," he warned, could lead to a new mediocrity; it could also issue in a new kind of excellence. For those who doubted this, and there were always some, Europe seemed the lost paradise, the civilized refuge to repair to from America's bustle and clamor.

The United States began to grow somewhat more sedate, possibly more reflective, reportedly more intellectual, early in the twentieth century. When a wellborn New Yorker came to the presidency, imagining himself a man of the West, and acting as every red-blooded American was supposed to do, the lines of change were already dis-

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cernible, nowhere perhaps more so than in the White House itself. Presidential power grew; so, also, did the power of wealth. The institutions of capitalist America were consolidated: giant corporations; prestigious banks; great universities; a vast new network of museums, libraries, symphony orchestras, and the like. The country appeared to need more highly trained individuals and there were ample funds from private and public sources to sustain individual opportunity. The Great War, the depression, Hitler's persecutions, and World War II contributed certainly to a recognition of the value of intelligence, to make it seem all the more necessary. American science profited enormously from all these developments. Only in recent years, partly because of Vietnam, but also because of nuclear weapons, environmental pollution, hunger, and the like, have wholly new ethical concerns been aired, asking, in effect, what science has done to cope with problems that in many instances it helped to create. In this new intellectual environment, the earlier near-universal enthusiasm for science is believed to have somewhat abated. There is today a more deliberate probing into how scientific discovery occurs, who determines what scientific inquiry shall be undertaken, how the technological products of science can be effectively regulated and controlled. A large number of moral and political issues involving science have come to the fore. These are increasingly discussed and debated by the mass media. Such discussion, however enlightening, cannot substantially increase the public's knowledge of the complexities and beauty of science. Nor, if the truth be told, can it diminish scientific illiteracy in any meaningful sense of the term.

One denigrates neither television nor museums, magazines nor journals—to the extent that each is partially or significantly preoccupied with matters scientific—when one says that the only institutions that can create meaningful scientific competence for great numbers of Americans today are the nation's schools, colleges, and universities. Only they are equipped to disseminate the scientific knowledge on which an individual is able to build, as employment, family, and civic obligations may require him to do. This does not imply that individuals—adolescents and adults—cannot be taught technological trades without prior scientific education, or that learning is valuable only when it is provided by an institution that calls itself a school or university; it is simply that under present conditions, and for the foreseeable future, scientific competence will be most easily acquired and most competently judged in educational institutions.

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The problem, obviously, is to make this happen. For those who imagine that it will be easy, that it depends primarily on the willingness of the federal government to expend monies for such purposes, the future will almost certainly be disillusioning. The achieving of significantly higher levels of scientific competence by substantial numbers in the population is certain to be slow, requiring, in the first instance, a substantially different perspective on science by students, teachers, parents, and employers. This presupposes some understanding of why science is worth knowing, why mastering certain fundamentals is not beyond the capacity of ordinary mortals, of active, healthy children. It is precisely because we do not live in placid times—that none of us does, whether we are able to claim the security that comes from a stable family and a comfortable home, or whether we are forced to acknowledge that we have rarely known either—and that this is as true for those who teach as for those who learn, that we must begin by recognizing that science is not a settled thing, a collection of formulas that wait to be committed to memory, that once learned will be possessed forever. Scientific literacy is but an aspect of literacy more generally; scientific learning is a necessary part of general learning.

The American educational system is not highly centralized. There is no ministry of education in Washington that determines what the curriculum will be, what textbooks will be used, what laboratory exercises will be required. Indeed, there are fifty state systems; beyond these, vast liberties are extended to the individual cities and towns. There is no reason for New York schools to imitate those of California, in science or in any other subject, and no reason why schools in Houston cannot adopt practices that are not favored in Dallas. Independent schools, seeking to legitimate fees that seem always to go higher, would do well to consider what they can do to improve their instruction in science and mathematics, and how that improved instruction may relate to improved instruction in other disciplines. The links may be more subtle than are commonly admitted. Building new and expensive laboratories, buying yet additional computers—these are the acts of educational entrepreneurs, doing what students also do when they personality-hunt, asking for a speech that will be reported, adding to the institution's celebrity. Such publicity is rarely harmful. Still, it is no substitute for the creation of a program of educational value that depends on something other than entrepreneurship.

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America's schools, while accepting the necessity of helping to create an ethos—a socially responsible one—have been largely neglectful of creating another that has intellectual development and achievement as its principal plank. There is no possibility of instituting a blanket curriculum in the country—there is no need for one—but there is a need for introducing systems of evaluation that will accurately register how effective individual schools are in providing instruction. Today, examinations are private, internal school affairs, instituted mostly to test students, frequently doing so haphazardly, disingenuously, and naively. Such examinations tell nothing about the schools, about their own teaching performance. Again, there is evasion, institutional evasion. Until systems of regional and even national testing are instituted, which test accomplishment rather than aptitude, there is no possibility of knowing how much algebra is being learned, and where, or how much any other subject is being pursued and mastered. The present system is a shield, protecting not the student but the system. This is secrecy that has no justification, that serves no valid educational purpose.

Schools, colleges, and universities belong to "leagues," not always acknowledged as such, but generally known to those inside. Institutions recognize their real rivals and generally accept the need to compete with them. This is as true in education as in athletics; there is as much a pecking order in the first league as in the second, though the standings are not always officially proclaimed in alumni announcements. It is usually known if school A is doing substantially better in its mathematics instruction than school B; how school O is doing may be largely irrelevant to both, if this school is thought to belong to a different "league." Finding exemplary schools in each category, persuading those principally responsible for "hard option" instruction in rival schools to seek parity with them, pressing the best to try to do what is being done in the "league" above by providing the teacher training and the curriculum development that will encourage such institutional movement, will never be easy. But it will always be possible, in certain institutions, at certain times.

Such efforts must invariably rely on the cooperation of teachers, prepared to understand how their own professional lives can be altered by a larger commitment to certain kinds of excellence. While contractual arrangements in various public school systems may make impossible salary differentials based on professional qualifications other than those of seniority, such union rules are not universal. Systems of certification, based on evidence of tested competence, togeth-

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er with other more subtle (more subjective) judgments of teaching ability, ought to make it possible for significant salary differences to exist, with teachers encouraged to secure additional education, so that they may serve more effectively. The career ladder of a teacher in a good school ought to have many rungs, with titles, distinctions, and compensation adequate to each, reflecting institutional judgment and approval.

Calendar reform ought to be seriously contemplated. Ten-week holidays in the summer may have been admirably suited to an agricultural society that required young "hands" in the fields. It makes no sense whatever in the twentieth century, least of all for families where both parents are employed. The situation is even more outmoded in many independent schools, where school holidays through the year may extend for as much as sixteen or even eighteen weeks. Long vacations are thought to be partial compensation for low salaries. They are not, particularly when it is the student who is the principal loser through this arrangement.

A deliberate effort ought to be made to establish where teachers are exploited, where their salaries, hours of work, pension rights, and the like are substantially lower than those of others who teach. Where it can be established that they are disadvantaged, additional compensation ought to be provided; where they appear to be "privileged," there is an added incentive for them to define their roles in such a way as to appeal to young men and women not now contemplating teaching as a profession. The justification for higher salaries for some is precisely that it may serve as an inducement to others, to those who are wanted and needed for the profession.

How, then, does this differ from other programs that call for greater effort—greater rigor, precision, and application—by the young? First, it does not start with fear, with the illusion that nations outside are challenging the United States, that our national purpose is to "beat" them. It interprets our problem as an educational problem, not a science problem. It suggests that our failure has been internal, an unwillingness to take seriously the nation's obligations to its children, which is neither to cosset them nor to hold them in contempt—least of all to fear them—but to acknowledge that educating them will always be difficult, that it can only prove effective when it is embarked upon with some measure of idealism and hope. An educational system that aspires to be democratic will not simply instruct in civics; it will also understand the importance of offering math and

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physics, biology and history, foreign languages, and that old staple, English.

Such a perception of the country's educational needs can never start with a concern as to whether the Russians are "beating" us militarily (or diplomatically), whether the Japanese are doing us in economically. It will avoid scare tactics of the kind, all too familiar today, that remind us that in the ten-year Soviet polytechnic school curriculum, calculus is studied in the last two years, and that this translates into 5 million Soviet students graduating each year with this level of mathematical competence. Second, it will not dwell on the fact that only 105,000 Americans take even a single year of calculus—this having been true in 1980.[2] Does this suggest that such differences are of no consequence? Not at all. Only, that in an American school science curriculum, created for this kind of society, calculus is unlikely to emerge as the educational passport for professional success. While engineering in the Soviet Union is the profession with multiple career opportunities, law and business serve something of the same purpose in the United States. An American civilian economy that relies on professional training for such occupations is never going to award calculus the importance the Soviets do, though it may sometimes wish that it could.

What, then, should an American science curriculum emphasize, for children, adolescents, and young adults? Would an earlier generation of Americans have been ashamed to say: knowledge of the natural universe; capacity to construct and operate simple mechanisms, to build and tend uncomplicated machines; some comprehension of space and time; and appreciation for the mysteries of life, for the beauties of mathematical proof? To construct a modern curriculum, to be concerned with teaching statistical probability as well as Euclidian geometry, and to know how much attention needs to be given to each, is obviously to engage in the kinds of intellectual exercises that ought to preoccupy educators—not all of them, obviously, but a number substantially larger than any who now think this to be one of their major responsibilities and pleasures. So long as teaching is mocked, so long as its principal obligations are thought to be disciplinary, the profession can never be awarded the status that it merits. The time has come when both teaching and parenting need again to be seen in a perspective that is not mechanical, that is not learned through a simple consulting of "how to" manuals.

Literacy is a worthy objective; we would do well to keep it. It is right for the country to look at the scientific illiteracy of millions, to

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ask whether such ignorance is either justified or necessary. It will not be remedied through the purchase of computers; it will be helped through the training of teachers. To be literate in science is not to be isolated, to discover oneself ensconced in an occupational box labeled "science." Rather, it is to be able to reach out to others, in the arts, the humanities, the social sciences, to have some small purchase on modernity in a way that very few can claim today. This is a challenge appropriate to young people, but it is not one that they are able to create for themselves.

To construct proper systems of scientific education for the young must involve the young, engage their energies and interests. It must also involve others, particularly those who understand that there are well over 16,000 school districts in the country, almost 20,000 elementary and secondary schools under private control, and several thousand institutions, public and private, that call themselves colleges and universities. This astonishing multiplicity of institutions creates the possibility of immense educational experimentation. Until governors and mayors can be made to see the advantages to themselves—to their own careers—of a more competent citizenry, until they can see the concrete economic advantages to their states and communities, they will never make scientific or other literacy their principal concern. Nor will property owners, all those who pay taxes, individuals and corporations, who need to know why a reputation for good schools can only help them—even in their pocketbooks, making their houses more valuable, their industries more productive. It will not happen everywhere at once. It cannot happen in that way.

The success of any really fundamental educational reform will depend in the United States in great part on local initiative, instigated by educators, parents, businessmen, property owners, and even, among adolescents and young adults, by the students themselves. They are the ones who have been fobbed off with what is rarely good enough; they are the ones who are humiliated by an imposed incompetence that they cannot be wholly unaware of. They are capable of doing a great deal more; the educational system—with all its anachronisms—is capable of doing a great deal better. The federal government can help in crucial ways; so, also, must other institutions—educational at all levels—but also those committed to the development of American commerce and industry. In this effort, those concerned with the moral improvement of society must also acknowledge their role. The issue of scientific literacy ought not to be equated

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with competence in either calculus or the computer—though both have incontestable value—but with a larger capacity, which is nothing less than to know how remarkable it is to understand and appreciate variety, how splendid are its manifestations in nature and in society, and how incomparable are the school's opportunities to teach such things. A science curriculum expressing its own excellence, incorporated in a larger curriculum with its own values and methods, each having some legitimate regard for the other, is what is most desperately needed at this time. We are again looking for good schools capable of providing good education, suited to a twentieth century American democracy unashamed of its eighteenth century purpose, the creation of a "virtuous" people.

ENDNOTES

[1]*New York Times,* March 1, 1983, p. A23.
[2]*Science 80,* 1 (6) (September/October 1980): 17.

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